APPENDIX G-1

Physical Oceanographic Evaluation of Long Island and Block Island Sounds

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October, 2001

United States
Environmental
Protection Agency

US Army Corps
Of Engineers
New England District
696 Virginia Road
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LONG ISLAND SOUND

DREDGED MATERIAL DISPOSAL EIS

Physical Oceanographic Evaluation of Long Island Sound and Block Island Sound

October, 2001

LIS-2001-F,A,S08-O

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CONTENTS

SECTION **PAGE**

ACRONYMNS AND ABBREVIATIONS

EXECUTIVE SUMMARY ES-1

1.0 INTRODUCTION 1-1

1.1 BACKGROUND 1-1
1.1.1 The Environmental Impact Statement (EIS) Process 1-1
1.1.1 The Role of Physical Oceanographic Characterization in the EIS Process 1-2
1.1 PREVIOUS PHYSICAL OCEANOGRAPHIC STUDIES OF LONG ISLAND AND BLOCK ISLAND SOUNDS 1-3
1.1 PURPOSE AND SCOPE OF THE SPRING 2001 DATA COLLECTION PROGRAM 1-4
1.1 REPORT ORGANIZATION 1-5

2.0 HISTORIC CHARACTERIZATION OF HYDRODYNAMICS, SEDIMENTS, AND STORM EVENTS IN LONG ISLAND SOUND AND BLOCK ISLAND SOUND 2-1

2.1 LONG ISLAND SOUND 2-1
2.1.1 Hydrodynamics 2-1
2.1.2 Sedimentary Environment 2-3
2.2 BLOCK ISLAND SOUND 2-5
2.2.1 Hydrodynamics 2-5
2.2.2 Sedimentary Environment 2-6
2.3 REVIEW OF THE METEOROLOGICAL RECORD TO IDENTIFY WORST-CASE STORMS 2-7
2.3.1 Methodology 2-7
2.3.2 Results 2-8
2.4 REFERENCES 2-10

3.0 SUMMARY OF AVAILABLE PHYSICAL OCEANOGRAPHY DATA 3-1

3.1 LONG ISLAND SOUND 3-1
3.1.1 Overview of Historical Data 3-1
3.1.2 Analysis of Previously Collected Data 3-9
3.2 BLOCK ISLAND SOUND 3-17
3.3 SUMMARY 3-19
3.4 REFERENCES 3-20

CONTENTS (Cont'd)

4.0 SPRING 2001 DATA COLLECTION PROGRAM 4-1

4.1 STUDY OBJECTIVES, DESIGN AND APPROACH 4-1
4.1.1 Introduction 4-1
4.1.2 Study Objectives 4-2
4.1.3 Study Design 4-2
4.1.4 Rationale for Selecting Data Collection Locations 4-3
4.2 FIELD PROCEDURES AND INSTRUMENTATION 4-8
4.2.1 Water Column Water Velocity Measurement Instrumentation 4-9
4.2.2 Near-Bottom Water Velocity Measurement Instrumentation 4-9
4.2.3 Near-Bottom Turbidity Measurement Instrumentation 4-10
4.2.4 Surface Wave and Tidal Elevation Measurement Instrumentation 4-10
4.2.5 CTD Profiles 4-10
4.2.6 Navigation and Positioning 4-11
4.2.7 Deployment and Recovery of Instrument Suites 4-11
4.2.8 Calibration of Instrumentation 4-12
4.3 REFERENCES 4-12

5.0 SPRING 2001 DATA COLLECTION PROGRAM DATA SUMMARY 5-1

5.1 DATA INVENTORY AND QUALITY ASSESSMENT 5-3
5.1.1 Water Velocities 5-3
5.1.2 Waves 5-5
5.1.3 Tidal Height 5-5
5.1.4 Turbidity 5-6
5.1.5 Temperature 5-6
5.1.6 Temperature and Salinity Profiles 5-7
5.1.7 Wind and Air Temperature 5-7
5.2 DATA PROCESSING 5-7
5.2.1 Water Velocity Time Series 5-8
5.2.2 Tidal Height 5-8
5.2.3 Waves 5-9
5.2.4 Wind 5-9
5.2.5 Database of Spring 2001 and Historical Physical Oceanography Data 5-9
5.3 DATA ANALYSIS AND INTERPRETATION 5-10
5.3.1 Meteorological Data 5-10
5.3.2 Tidal Height 5-11

CONTENTS (Cont'd)

5.3.3 CTD Data 5-11
5.3.4 Turbidity 5-12
5.3.5 Bottom Water Temperature 5-13
5.3.6 Water Velocity 5-13
5.3.7 Waves 5-37
5.4 REFERENCES 5-37

6.0 CONCLUSION 6-1

6.1 REVIEW AND EVALUATION OF PREVIOUSLY COLLECTED DATA 6-1
6.2 SPRING 2001 DATA COLLECTION PROGRAM 6-2

APPENDICES

A SPECIFICATION OF A WORST-CASE STORM EVENT IN LONG ISLAND/BLOCK ISLAND SOUND

B HYDRODYNAMIC CIRCULATION OF BLOCK ISLAND SOUND: LITERATURE REVIEW AND ANALYSIS

LIST OF TABLES

NUMBER	TITLE
Table 2-1	Percent Exceedance for West Winds
Table 2-2	Percent Exceedance for South Winds
Table 2-3	Percent Exceedance for East Winds
Table 3-1	Seasonal Hydrodynamic Data Collection Summary
Table 3-2	Dates of NOS Deployments
Table 3-3	Summary of NOS Data Collection Activities
Table 3-4	Summary of SUNY Velocity Data Recovery
Table 3-5	Summary of City of New York Meter Deployments
Table 3-6	NOS Stations Presented in Detailed analysis
Table 3-7	Tidal Ellipse Parameters for Bottom, Middle and Surface Currents NOS Long Island Sound Oceanographic Survey, 1988-1990
Table 4-1	Instrument Suite Deployment Locations
Table 4-2	Synoptic Survey Transect Locations
Table 4-3	Instrument Suite Deployed at Fixed Stations
Table 5-1	Summary of Measurements Performed at Fixed Stations
Table 5-2	Summary of Measurements Performed at Fixed Stations
Table 5-3	Tidal Constituents Used for Harmonic Decomposition of Water Velocities
Table 5-4	Stations Selected for Complete Presentation Within Each Basin
Table 5-5	Descriptive Statistics of Water Velocity Magnitude
Table 5-6	Bottom Water Velocity Properties for Flood and Ebb Tides
Table 5-7	Tidal Ellipse Parameters for Bottom, Middle and Surface Currents ENSR Long Island Sound Data Collection Program, Spring 2001
Table 5-8	Relative Energy of Physical Processes During Spring 2001 Data Collection Program
Table 5-9	High Frequency Water Velocity Statistics (cm/s)
Table 5-10	Descriptive Statistics of Water Velocity Magnitude During Event 1 (March 20 - March 24, 2001)
Table 5-11	Descriptive Statistics of Water Velocity Magnitude During Event 2 (May 1 - May 5, 2001)
Table 6-1	Descriptive Statistics of Current Magnitude
Table 6-2	Summation of Peak Major Axis Near-Bottom Water Velocity Components

LIST OF FIGURES

NUMBER **TITLE**

Figure 2-1 Map of Long Island Sound with Bathymetry
Figure 2-2 Predicted Bottom Currents at 1 m Above the Bottom
Figure 2-3 Distribution of Surficial Sediments in Long Island Sound
Figure 2-4 Regional Distribution of Sea Floor Sedimentary Environments in Long Island Sound
Figure 2-5 Block Island Sound and Surrounding Features. Rhode Island Sound to the East, Long Island Sound to the West, and New York Bight (Continental Shelf) to the South
Figure 2-6 Bathymetry of Block Island Sound Showing Moraine Ridges and Central Plain
Figure 2-7 Peak Flood Tide Currents Through Block Island Sound, Three Hours After Slack Tide at the Race
Figure 2-8 Peak EBB Currents (at the Surface) Through Block Island Sound, Three Hours After Slack at the Race
Figure 2-9 Map of Surface Currents From the Codar System Run By Universities of Rhode Island and Connecticut for February 15, 2001 at 0900 Hours GMT
Figure 2-10 Map of Surficial Sediment Distribution in Block Island Sound
Figure 2-11 Map of Block Island sound with Percentages of Silt Found in Bottom Sediments
Figure 2-12 Map of Long Island And Block Island Sounds Showing the Locations of Wind Data Sources ..
Figure 3-1 Compilation of Hydrodynamic Sampling Locations in Long Island and Block Island Sounds
Figure 3-2 Spring Hydrodynamic Sampling Locations
Figure 3-3 Summer Hydrodynamic Sampling Locations
Figure 3-4 Fall Hydrodynamic Sampling Locations
Figure 3-5 Winter Hydrodynamic Sampling Locations
Figure 3-6 NOS Sampling Locations
Figure 3-7 An Example of Water Velocity Measurements at NOS08
Figure 3-8 Location of SUNY Transects
Figure 3-9 City of New York Measurement Locations
Figure 3-10 Western Long Island Sound with Previous Sampling Locations Indicated
Figure 3-11 Central Long Island Sound with Previous Sampling Locations Indicated
Figure 3-12 Eastern Long Island Sound with Previous Sampling Locations Indicated
Figure 3-13 Water Velocity Magnitude and Related Measurements Collected During Deployment NOS07-02
Figure 3-14 Water Velocity Magnitude and Related Measurements Collected During Deployment NOS08-01
Figure 3-15 Water Velocity Magnitude and Related Measurements Collected During Deployment NOS09-01

LIST OF FIGURES (Cont'd)

NUMBER **TITLE**

Figure 3-16 Water Velocity Magnitude and Related Measurements Collected During Deployment NOS13-02
Figure 3-17 Water Velocity Magnitude and Related Measurements Collected During Deployment NOS21-01
Figure 3-18 Directional Water Velocity and Related Measurements Collected During Deployment NOS07-02
Figure 3-19 Directional Water Velocity and Related Measurements Collected During Deployment NOS08-01
Figure 3-20 Directional Water Velocity and Related Measurements Collected During Deployment NOS09-01
Figure 3-21 Directional Water Velocity and Related Measurements Collected During Deployment NOS13-02
Figure 3-22 Directional Water Velocity and Related Measurements Collected During Deployment NOS21-01
Figure 3-23 Current Rose Diagrams for Deployment NOS07-02
Figure 3-24 Current Rose Diagrams for Deployment NOS08-01
Figure 3-25 Current Rose Diagrams for Deployment NOS09-01
Figure 3-26 Current Rose Diagrams for Deployment NOS13-02
Figure 3-27 Current Rose Diagrams for Deployment NOS21-01
Figure 3-28 Tidal Current Ellipses at for Deployment NOS07-02
Figure 3-29 Tidal Current Ellipses at for Deployment NOS08-01
Figure 3-30 Tidal Current Ellipses at for Deployment NOS09-01
Figure 3-31 Tidal Current Ellipses at for Deployment NOS13-02
Figure 3-32 Tidal Current Ellipses at for Deployment NOS21-01
Figure 3-33 Components of Water Velocity Measurements Collected During Deployment NOS07-02
Figure 3-34 Components of Water Velocity Measurements Collected During Deployment NOS08-01
Figure 3-35 Components of Water Velocity Measurements Collected During Deployment NOS09-01
Figure 3-36 Components of Water Velocity Measurements Collected During Deployment NOS13-02
Figure 3-37 Components of Water Velocity Measurements Collected During Deployment NOS21-01
Figure 3-38 Water Velocity Measurements Collected During Deployment NOS08-01 (Event 1)
Figure 3-39 Water Velocity Measurements Collected During Deployment NOS09-01 (Event 1)
Figure 3-40 Wind and Sub-Tidal Currents During Deployment NOS08-01 (Event 1)
Figure 3-41 Wind and Sub-Tidal Currents During Deployment NOS09-01 (Event 1)
Figure 3-42 Wind and Sub-Tidal Current Rose Diagrams for Deployment NOS08-01 (Event 1)
Figure 3-43 Wind and Sub-Tidal Current Rose Diagrams for Deployment NOS09-01 (Event 1)
Figure 3-44 Water Velocity Measurements Collected During Deployment NOS08-01 (Event 2)

LIST OF FIGURES (Cont'd)

NUMBER **TITLE**

Figure 3-45 Water Velocity Measurements Collected During Deployment NOS09-01 (Event 2)
Figure 3-46 Wind and Sub-Tidal Currents During Deployment NOS08-01 (Event 2)
Figure 3-47 Wind and Sub-Tidal Currents During Deployment NOS09-01 (Event 2)
Figure 3-48 Wind and Sub-Tidal Current Rose Diagrams for Deployment NOS08-01 (Event 2)
Figure 3-49 Wind and Sub-Tidal Current Rose Diagrams for Deployment NOS09-01 (Event 2)
Figure 4-1 Location of Transects and Fixed Stations in Western Long Island Sound
Figure 4-2 Location of Transects and Fixed Stations in Central Long Island Sound
Figure 4-3 Location of Transects and Fixed Stations in Eastern Long Island Sound and Block Island Sound
Figure 4-4 Schematic Diagram of Bottom Mounted Instrumentation Configuration
Figure 5-1 Comparison of Surface Tracking, Pressure and Orbital Velocity Derived Wave Spectra at Station 01
Figure 5-2 Climate Data Measured at Station BUZM3
Figure 5-3 Wind Rose Diagram for Spring 2000 Survey Period (Measured at BUZM3)
Figure 5-4 Water Pressure Measured in LIS/BIS Basins
Figure 5-5 Temperature Profiles Collected During Instrument Deployment and Retrieval
Figure 5-6 Salinity Profiles Collected During Instrument Deployment and Retrieval
Figure 5-7 Turbidity and Related Measurements Collected at Station 03
Figure 5-8 Turbidity and Related Measurements Collected at Station 04
Figure 5-9 Turbidity and Related Measurements Collected at Station 07
Figure 5-10 Turbidity and Related Measurements Collected at Station 09
Figure 5-11 Water Velocity Magnitude and Related Measurements Collected at Station 01
Figure 5-12 Water Velocity Magnitude and Related Measurements Collected at Station 04
Figure 5-13 Water Velocity Magnitude and Related Measurements Collected at Station 06
Figure 5-14 Water Velocity Magnitude and Related Measurements Collected at Station 10
Figure 5-15 Directional Water Velocity and Related Measurements Collected at Station 01
Figure 5-16 Directional Water Velocity and Related Measurements Collected at Station 04
Figure 5-17 Directional Water Velocity and Related Measurements Collected at Station 06
Figure 5-18 Directional Water Velocity and Related Measurements Collected at Station 10
Figure 5-19 Current Rose Diagrams for Station 01
Figure 5-20 Current Rose Diagrams for Station 04
Figure 5-21 Current Rose Diagrams for Station 06
Figure 5-22 Current Rose Diagrams for Station 10
Figure 5-23 Histograms of Near-Bottom Water Velocity Magnitudes
Figure 5-24 Tidal Ellipses at Station 01
Figure 5-25 Tidal Ellipses at Station 04

LIST OF FIGURES (Cont'd)

NUMBER **TITLE**

Figure 5-26 Tidal Ellipses at Station 06
Figure 5-27 Tidal Ellipses at Station 10
Figure 5-28 Relative Energy of Currents Attributable to Physical Processes
Figure 5-29 Rose Diagrams of High-Frequency Currents at Each of 10 Stations
Figure 5-30 High Frequency Water Velocity Analysis for Station 01, with Noise Levels and Associations to Winds
Figure 5-31 High Frequency Water Velocity Analysis for Station 04, with Noise Levels and Associations to Winds
Figure 5-32 High Frequency Water Velocity Analysis for Station 06, with Noise Levels and Associations to Winds
Figure 5-33 Rose Diagrams of Sub-Tidal Currents at Each of 10 Stations
Figure 5-34 Rose Diagrams of Sub-Tidal currents Separated into Two Frequency Bands
Figure 5-35 Transfer Function Between Along-Axis (East-West) Winds and Sub-Tidal Currents Observed at Station 01
Figure 5-36 Transfer Function Between Along-Axis (East-West) Winds and Sub-Tidal Currents Observed at Station 04
Figure 5-37 Sub-Tidal Processes Observed at Station 09 in Block Island Sound
Figure 5-38 Wind Event 1: Water Velocity Measurements Collected at Station 01
Figure 5-39 Wind Event 2: Water Velocity Measurements Collected at Station 01
Figure 5-40 Wind Event 1: Water Velocity Measurements Collected at Station 04
Figure 5-41 Wind Event 2: Water Velocity Measurements Collected at Station 04
Figure 5-42 Wind Event 1: Water Velocity Measurements Collected at Station 06
Figure 5-43 Wind Event 2: Water Velocity Measurements Collected at Station 06
Figure 5-44 Wind Event 1: Water Velocity Measurements Collected at Station 10
Figure 5-45 Wind Event 2: Water Velocity Measurements Collected at Station 10
Figure 5-46 Wind Event 1: Sub-Tidal Water Velocities at Station 01
Figure 5-47 Wind Event 2: Sub-Tidal Water Velocities at Station 01
Figure 5-48 Wind Event 1: Sub-Tidal Water Velocities at Station 04
Figure 5-49 Wind Event 2: Sub-Tidal Water Velocities at Station 04
Figure 5-50 Wind Event 1: Sub-Tidal Water Velocities at Station 06
Figure 5-51 Wind Event 2: Sub-Tidal Water Velocities at Station 06
Figure 5-52 Wind Event 1: Sub-Tidal Water Velocities at Station 10
Figure 5-53 Wind Event 2: Sub-Tidal Water Velocities at Station 10
Figure 5-54 Wind Event 1: Rose Diagrams of Wind and Sub-Tidal Currents at Station 01
Figure 5-55 Wind Event 2: Rose Diagrams of Wind and Sub-Tidal Currents at Station 01
Figure 5-56 Wind Event 1: Rose Diagrams of Wind and Sub-Tidal Currents at Station 04

LIST OF FIGURES (Cont'd)

NUMBER **TITLE**

Figure 5-57 Wind Event 2: Rose Diagrams of Wind and Sub-Tidal Currents at Station 04
Figure 5-58 Wind Event 1: Rose Diagrams of Wind and Sub-Tidal Currents at Station 06
Figure 5-59 Wind Event 2: Rose Diagrams of Wind and Sub-Tidal Currents at Station 06
Figure 5-60 Wind Event 1: Rose Diagrams of Wind and Sub-Tidal Currents at Station 10
Figure 5-61 Wind Event 2: Rose Diagrams of Wind and Sub-Tidal Currents at Station 10
Figure 5-62 Water Velocity Magnitude at Transect TR01 (File 14, Direction S-N)
Figure 5-63 Water Velocity Magnitude at Transect TR02 (File 12, Direction S-N)
Figure 5-64 Water Velocity Magnitude at Transect TR03 (File 01, Direction N-S)
Figure 5-65 Water Velocity Magnitude at Transect TR04 (File 03, Direction S-N)
Figure 5-66 Water Velocity Magnitude at Transect TR05 (File 08, Direction N-S)
Figure 5-67 Water Velocity Magnitude at Transect TR06 (File 20, Direction N-S)
Figure 5-68 Water Velocity Magnitude at Transect TR07 (File 24, Direction S-N)
Figure 5-69 Water Velocity Magnitude at Transect TR08 (File 16, Direction N-S)
Figure 5-70 Water Velocity Magnitude at Transect TR09 (File 17, Direction N-S)
Figure 5-71 Water Velocity Magnitude at Transect TR10 (File 38, Direction S-N)
Figure 5-72 Water Velocity Magnitude at Transect TR11 (File 32, Direction N-S)
Figure 5-73 Water Velocity Magnitude at Transect TR12 (File 26, Direction S-N)
Figure 5-74 Water Velocity Magnitude at Transect TR13 (File 30, Direction N-S)
Figure 5-75 Water Velocity Magnitude at Transect TR14 (File 39, Direction S-N)
Figure 5-76 Water Velocity Magnitude at Transect TR15 (File 28, Direction W-E)
Figure 5-77 Water Velocity Magnitude at Transect TR16 (File 50, Direction S-N)
Figure 5-78 Water Velocity Magnitude at Transect TR17 (File 51, Direction N-S)
Figure 5-79 Water Velocity Magnitude at Transect TR18 (File 53, Direction S-N)
Figure 5-80 Water Velocity Magnitude at Transect TR19 (File 45, Direction S-N)
Figure 5-81 Water Velocity Magnitude at Transect TR20 (File 55, Direction N-S)
Figure 5-82 Water Velocity Magnitude at Transect TR21 (File 19, Direction E-W)
Figure 5-83 Waves Measurements Collected at Station 01
Figure 5-84 Waves Measurements Collected at Station 04
Figure 5-85 Wave Height Directional Frequency Distribution at Stations 01 and 04

Figure 6-1 Histograms of Near-Bottom Water Velocity Magnitudes

ACRONYMNS AND ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
BIS	Block Island Sound
CCMP	Comprehensive Conservation Management Plan
cm/s	centimeters per second
CTD	conductivity, temperature, and depth
CWA	Clean Water Act
DAMOS	Disposal Area Monitoring System
DGPS	Differential Global Positioning System
EIS	Environmental Impact Statement
GIS	Geographic Information System
GMT	Greenwich Mean Time
kg/year	kilogram per year
LIS	Long Island Sound
LISOP	Long Island Sound Oceanography Project
LISS	Long Island Sound Study
m	meter
µm	micrometer
MPRSA	Marine Protection, Research and Sanctuaries Act
m/s	meters per second
NEPA	National Environmental Policy Act
NIST	National Institute of Standards and Technology
nm	nautical miles
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
SAIC	Science Applications International Corporation
SUNY	State University of New York
OBS	Optical Backscatter Nephelometer
ppt	parts per thousand
QAPP	Quality Assurance Project Plan
the Corps	The United States Army Corps of Engineers
UCONN	University of Connecticut
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

EXECUTIVE SUMMARY

E.1 INTRODUCTION

The purpose of this report is to document the physical oceanographic characteristics of Long Island Sound (LIS) and Block Island Sound (BIS) in support of the Long Island Sound Environmental Impact Statement (EIS). The report provides a summary of physical oceanographic characteristics throughout the study area and is designed to support the evaluation of regions within the study domain for suitability for dredged material disposal from a physical oceanographic perspective.

Information on physical oceanographic characteristics was obtained through evaluation of existing literature and existing data, and through performance of a major field data collection program in the spring of 2001. Quantification of water column and near-bottom water velocities and the factors leading to maximum near-bottom water velocities were focus areas of the Spring 2001 study.

E.1.1 The Environmental Impact Statement (EIS) Process

The U.S. Environmental Protection Agency, Regions I and II (USEPA, Regions I and II), and U.S. Army Corps of Engineers, New England District (USACE or the Corps, New England District), are proceeding with the preparation of an Environmental Impact Statement in compliance with the National Environmental Policy Act (NEPA). The EIS will consider the potential designation of one or more dredged material disposal sites in the waters of LIS and BIS consistent with the provisions of Section 102 (c) of the Marine Protection, Research, and Sanctuaries Act (MPRSA) and 40 CFR 230.80 of EPA's regulations under Section 404 of the Clean Water Act (CWA).

The open water component of the EIS process may be described as a series of the following three evaluation phases:

1. *Siting feasibility analysis.* Data will be collected and used to assist in determining the feasibility of locating disposal sites anywhere in LIS and/or BIS.

2. *Site-screening.* The site-screening process requires characterization of the study area in terms of several critical factors including hydrodynamics, potential for ecological impact, and economics.

3. Site-specific alternative disposal site evaluation. For each site selected during the site-screening process, a site-specific evaluation will be performed using site-specific hydrodynamic, as well as other, data.

Potential dredged material disposal sites are evaluated in terms of the three phases outlined above, using the appropriate data from the physical oceanographic characterization and other data collection efforts.

E.1.2 The Role of Physical Oceanographic Characterization in the EIS Process

Physical oceanographic characterization is an important component of the EIS process because the extent of dredged material transport in the open water environment is dependent on hydrodynamics. Specifically, ambient water currents can transport dredged material suspended in the water column during disposal events and can re-suspend and transport dredged material from the seafloor via scouring following disposal events. Because of the importance of the physical oceanographic characteristics of a site with respect to the potential for dredged material transport, specific regulatory criteria, which should be evaluated as part of the site selection process, exist for assessing potential disposal sites with respect to site hydrodynamic characteristics. These criteria focus on the potential for transport of dredged material away from the disposal site to adjacent resource areas (e.g., fisheries and shorelines). Evaluation of the potential for transport includes an assessment of the prevailing water velocity magnitude and direction.

E.1.3 Purpose of the Present Study

The objective of the hydrodynamic field data collection program was to fill the data gaps in the historical record and provide the data required to support the EIS evaluation. Field measurement data from the program are applicable to support evaluation of siting feasibility and site-screening by comparing specific hydrodynamic measurements to criteria established for acceptability in terms of disposal sites characteristics. For site-screening, collected measurements from the program are applicable to support a spatial suitability ranking and selection process. Site-specific data characterization of alternative disposal sites are applicable to support site-specific dredged material transport assessment.

The hydrodynamic field program was designed to capture maximum energy or “worst-case” hydrodynamic conditions at numerous locations throughout the study area. Worst-case conditions are defined as those conditions with maximum potential for dredged material transport associated with the following two primary scenarios:

- Potential dredged material transport during disposal events via dispersion and transport associated with maximum water column currents and,
- Potential dredged material transport following disposal via re-suspension from the sea floor and transport associated with near-bottom currents.

The Spring 2001 Data Collection Program was designed to capture water column and near-bottom water velocities during the spring period when some of the worst-case storm and wind conditions are generally expected to occur. The field program consisted of the following two major components: (1) the deployment of bottom-based, state-of-the-science instrument suites to measure hydrodynamics continuously for a period of 2 months at 10 selected locations and (2) a synoptic, boat-based survey performed at 21 transects to compliment long-term data collection by providing spatial characterization at selected times.

E.2 HISTORIC CHARACTERIZATION OF HYDRODYNAMICS, SEDIMENTS, AND STORM EVENTS IN LONG ISLAND AND BLOCK ISLAND SOUNDS

E.2.1 Long Island Sound Hydrodynamics and Sedimentary Environment

Long Island Sound is approximately 90 miles long and 15 miles wide and oriented along a roughly east-west axis with open ocean exchange at eastern and western boundaries. The mean depth of the Sound is 20 meters and the maximum depth is 90 meters near its easterly boundary. Water movement in LIS is primarily driven by tidal forcings, with wind, storm events and freshwater inflows contributing to varying degrees. Storm events, producing wind-waves and establishing energetic flow regimes, combine with normal tidal forcings to create maximum water velocities and "worst-case" conditions in terms of potential dispersion of dredged material. Specifically, sustained storm events featuring high winds along the axis of the Sound are expected to produce maximum bottom currents and result in the maximum potential for sediment re-suspension.

Water velocity magnitudes have been observed to be greatest in Eastern LIS and generally diminish with distance west. Tidal currents are generally oriented along the east-west axis of the Sound. Well-developed estuarine circulation has been observed in the Sound with fresher, less dense water flowing eastward along the surface, and saline water flowing westward along the bottom. This circulation pattern is affected by the degree of water column stratification which is determined by vertical density and temperature gradients. There is a general counter-clockwise circulation, with currents along the north shore heading to the west and currents along the south shore heading east. There is also evidence for several localized gyres within LIS.

A combination of previously obtained field measurements and model predictions have indicated that winds and density currents can have an important effect on current magnitude, adding substantially to the tidally-driven current. A modeling study conducted by the U.S. Geological Survey (USGS) predicted tidally-driven bottom currents of less than 20 cm/s in the western portion of the Sound, between 20-40 cm/s in the central Sound, 30-60 cm/s in the eastern Sound, and greater than 50 cm/s in the constriction at the eastern end of the Sound (Signell et al 1997, Signell et al 2000). Areas where the USGS model predicted bottom tidal currents greater than 30 cm/s corresponded to regions identified as erosional or non-depositional.

The bottom sedimentary environment of LIS is indicative of the movement and deposition of sediments due to local and regional geologic and oceanographic conditions. Four sedimentary environments have been identified: erosion or non-deposition; coarse-grained bedload transport; sediment sorting and reworking; and fine-grained deposition. At the eastern edge of the sound there is a large erosional or non-depositional area, likely caused by combination of strong tidal currents and a net westward movement of sediments into the sound. West of this region is an area of coarse-grained bedload transport, which is bordered on the western edge by a narrow area of sediment sorting and reworking. The seafloor in this region is primarily sand, transitioning gradually to marine mud towards the central basin. The central and western basins of the Sound are predominantly regions of fine-grained deposition. In localized areas, generally along north-south oriented shoals, there are regions of erosion or non-deposition and sediment sorting and reworking.

Turbidity measurements indicate that waves influence sediment transport around the margin of the Sound, up to depths of approximately 18 m. Within this margin, the bottom sediments are primarily sand, transitioning to mud with greater depths. In these deeper regions of the Sound, waves are expected to have little influence on sediments.

E.2.2 Block Island Sound Hydrodynamics and Sedimentary Environment

Block Island Sound is a semi-enclosed water body situated south of Rhode Island and east of Long Island and is primarily connected to LIS via a channel known as The Race. The Race is a deep, relatively narrow passage featuring highly-variable bathymetry and depths of up to 61 m. Plum Gut, located adjacent to The Race, is another major exchange channel with LIS. BIS exhibits variable bathymetry, with maximum depths on the order of 150 feet and ridges and shoals that range in depth from 9 m to 37 m. Bathymetric ridges as well as the Block Island land mass provide an important barrier to water transport and ocean waves, creating sheltered regions where conditions are relatively mild compared to open-ocean regions of the Atlantic.

Flood tides flow into BIS through Rhode Island Sound passage and Block Island Channel, converge within the Sound and then continue into The Race. The strongest flood currents are located within the deeper channels and around headlands such as Montauk Point, Point Judith, and Sandy Point, with weaker currents in the eastern-central portion of the Sound. The tide reverses during the ebb, and flows nearly in the opposite direction at all locations.

Studies of BIS show a two-layer estuarine system, with the upper surface responding strongly to wind stress, and the lower layer correlated more strongly to tidal forcing. In general, the upper layer demonstrates a net eastward drift with the lower layer showing net westward drift, into the estuary.

Sand is the most dominant sediment class within BIS, covering most of western and central regions. Fine-grained and very fine-grained sediments were found in the central area of the Sound, coincident with the weaker currents. Gravel was found in patches in the passages with the swiftest currents.

E.2.3 Review of the Meteorological Record to Identify Worst-Case Storms

Sustained strong-winds could provide additional energy that, when combined with tidal or density-induced currents, could potentially exceed the energy threshold for re-suspension and transport of sediments. To assist in assessing the impact of storm events on sediment transport, the historical wind data were analyzed to identify “worst-case” storms. Historical wind speed and direction data in LIS and BIS were obtained from three nearby land-based monitoring stations and one sea-based monitoring station. A simple screening procedure was developed to evaluate worst-case storms from the west, south, and east.

Winds from the west are the most frequent in this region, with winter winds predominantly from the northwest and summer winds predominantly from the southwest. The two worst-case west wind events represent the strongest west wind events in the historical data records in terms of peak speeds and event duration. The two events featured 15 to 20 m/s (33.6 to 44.7 mph) winds steadily from the west and persisting for several days.

Most of the strong south wind events occurred during the winter months, and were likely caused by extratropical storms. The strongest south wind events generally had peak speeds of approximately 20 m/s (44.7 mph); however, the event durations were relatively short due to rotation of winds during the storm events.

Strong east wind events normally correlate with strong winter northeast storms that are plentiful in the records. Two events, occurring on October 31, 1991 and December 11, 1992, were selected as worst-case east windstorms. Each of these events features winds with peak speeds of 25 m/s (55.9 mph) that persisted for several days.

Wind speed and direction time histories for three hurricanes, Gloria in September 1985, Bob in 1991, and Floyd in 1999, were obtained from the historic wind data. With the exception of Hurricane Bob whose eye passed directly over Block Island, these hurricanes were characterized by a rapid increase in wind speed and a steady rotation of winds throughout the event.

E.3 SUMMARY OF AVAILABLE PHYSICAL OCEANOGRAPHIC DATA

Previously collected physical oceanographic data on LIS and BIS were obtained from various sources, compiled, and evaluated. Numerous organizations were contacted as part of this process including the Long Island Sound Study Program, National Ocean Service (NOS), USGS, USEPA, USACE, City of New York, University of Connecticut (UCONN), and State University of New York (SUNY) at Stony Brook. The following major LIS and BIS physical oceanographic data sets were identified:

- NOS (1988-1990) throughout LIS and two stations in BIS
- SUNY (1989) throughout LIS

- City of New York (1995) Western LIS
- USACE (1997-1998) Eastern LIS
- UCONN (1980-present) throughout LIS

NOS, SUNY, and City of New York data sets have been obtained electronically and were included in the LIS hydrodynamic database. The USACE 1997-1998 data were collected at the New London disposal site are described in a draft report, but the electronic data set were not available. UCONN data were collected at numerous locations during numerous studies, but were not available to support the LIS EIS. Other historically collected hydrodynamic data on LIS were also not available electronically and were not included in the hydrodynamic database.

E.3.1 Historical Data Quality Summary

The NOS data set is by far the most extensive hydrodynamic data set available in the LIS region and the quality of the data set was found to be generally very good. SUNY data was found to be of marginal quality. Large periods of recorded data are degraded by biofouling and several meters failed to collect measurement of extended periods. The City of New York data was found to be of generally good quality and provides useful background data in the Western LIS region. The USACE data have not been reviewed, but are believed to be of good quality and to provide a strong contribution to the Eastern LIS region data set at the New London Disposal Site. Of the major water velocity data sets, only the USACE (1997-1998) data set included concurrent wave data collection.

E.3.2 Historical Spatial Data Coverage Summary

Existing LIS hydrodynamic data has primarily been collected at the eastern and western boundaries of the system. As a result, the best-characterized areas of the Sound, in terms of both the number and quality of data collection activities, are near the Race and near the East River. Hydrodynamic data collected at these locations indicate that they are not ideally suited to support EIS hydrodynamic characterizations because these areas are unlikely candidates as DM disposal sites.

In Western LIS the most directly applicable data appear to be City of New York data. The City of New York data was collected for a period of one year using a near-surface and a near-bottom water velocity meter. In addition, data were collected at 3 NOS stations during late spring and summer seasons when worst-case storm conditions are least likely to occur. These stations are generally located in areas unsuitable for dredged material disposal.

A paucity of data has been collected in the Central LIS region. In total, 1 SUNY transect and 2 NOS stations were located in this area. Both the SUNY and NOS data collection activities in Central LIS were performed during the summer season when worst-case storm events are least likely to occur. Also, the NOS stations are located in the relatively deep main channel areas that are not suitable for dredged material disposal.

Hydrodynamics have been relatively well characterized in Eastern LIS compared to the Central and Western regions. 6 NOS sampling locations, 6 SUNY sampling locations, 1 USACE sampling location, and numerous UCONN sampling locations have been situated in the Eastern LIS region. Relatively strong currents and a non-depositional sedimentary environment throughout much of the eastern region have been well documented.

Limited data has been collected in the BIS region. Some of the NOS stations were located in this area. Most of the data that does exist was collected at the open ocean boundaries and not in interior sections of the Sound.

E.3.3 Historical Seasonal Data Coverage

The largest seasonal data set was collected during the summer. In general, data from this season is least useful to support the EIS because disposal events generally do not occur during the summer season and “worst-case” hydrodynamic conditions are least likely to occur during the summer season.

E.3.4 Summary of Historical Data Gaps

Previously existing hydrodynamic data in LIS is generally suited to support Sound-wide hydrodynamic characterizations and modeling applications. In general, the existing data set is not as well suited to support the EIS hydrodynamic evaluation. Also, limited hydrodynamic data exists for BIS. Major data gaps identified in the review of existing data include the following:

- Little data collection activities focused on measurement of hydrodynamic conditions during storm events;
- Little wave data collected along with current measurements;
- Little data collected concurrently at different locations to support spatial characterization and comparison of hydrodynamic conditions;
- Little data collected in the Central Basin region in general and no recent data collected in the Central region during the fall/winter season;
- Little data collected in the Western and Central LIS regions, particularly at locations suitable for dredge material disposal; and
- Limited data exists for BIS.

Data collection activities performed during the Spring 2001 study were designed to address the data gaps listed above.

E.4 SPRING 2001 DATA COLLECTION PROGRAM

The Spring 2001 Data Collection Program was conducted in accordance with the program quality assurance document which was approved by EPA Region I, EPA Region II, and USACE prior to commencement of the field investigation. The goal of the program was to fill previously existing data gaps and to quantify hydrodynamic conditions relevant to evaluation of the potential for dredged material transport in support of the EIS process. Further, the study was designed to quantify hydrodynamic conditions throughout LIS and BIS concurrently to support spatial comparison of conditions at various locations. Lastly, the program was conducted during the spring season to obtain data during high-energy events when the potential for dredged material transport is greatest.

E.4.1 Study Design

The primary focus of the Spring 2001 Data Collection Program field program was the collection of water velocity measurements and quantification of the tidal, wave-induced, and storm-induced components of water velocity. To enable spatial comparison, measurements were collected concurrently throughout the entire study domain under a variety of tidal, wave, and storm conditions. Near-bottom water velocity and turbidity was also recorded to enable evaluation of bottom shear stress and the potential for associated sediment re-suspension via scouring.

The field program consisted of the following two major components:

- Task 1 – Two-month deployment of bottom-based instrument suites at 10 locations (Stations 01 and 02 in Western LIS; Stations 03, 04, and 05 in Central LIS; Stations 06, 07, and 08 in Eastern LIS; and Stations 09 and 10 in BIS) to continuously collect measurements of ambient water velocity, water level, and turbidity measurements throughout LIS and BIS. Instrument suites deployed at each location included measurement of near-bottom water velocity, water velocity measurements throughout the water column using an Acoustic Doppler Current Profiler (ADCP), surface waves, water surface elevations, and turbidity.
- Task 2 – Synoptic boat-based collection of water velocity measurements throughout the water column (using an ADCP) along 21 transects throughout LIS and BIS. Boat-based water velocity measurements were designed to provide extensive spatial coverage of water movement concurrently with measurements collected by the deployed, bottom-based instrument suites. Synoptic data collection was designed to extend the spatial coverage of the field program and to support evaluation of Sound-wide hydrodynamics.

Long-term hydrodynamic measurement locations and ADCP transects were selected based on several criteria including previously measured and predicted hydrodynamic and sediment characteristics. Measurement locations that were clearly inappropriate, such as very shallow areas near shore and very strong current areas near The Race, were excluded from consideration. Also, an attempt was made to represent the entire study domain in the sampling design by providing an approximately uniform spatial distribution in measurement locations.

E.4.2 Field Procedures and Instrumentation

State-of-the-science instrumentation suites were deployed at 10 sampling locations on the seafloor in LIS and BIS in March of 2001 and retrieved in May of 2001. In addition, a synoptic boat-based water velocity survey, featuring collection of measurements along 21 transects, was performed in May 2001.

Each deployed instrumentation suite contained an ADCP recording water velocity measurements (cm/sec) every 10-minutes throughout the water column, including three-dimensional (x-, y- and z-) vector components at each 2 meter depth interval. Each instrument suite also included a point-measurement acoustic current meter collecting water velocity measurements 1 meter above the sea floor, a water level gauge, and a turbidity (or optical backscatter) sensor. All of these instruments at each of the 10 sampling locations were synchronized to collect measurements every 10 minutes for a two-month period. At 3 stations (01, 04 and 07) wave burst data was collected every 10 minutes for the two month period.

Water column water velocity measurements were collected and recorded using RD Instruments ADCP Workhorse Sentinel at 300, 600 and 1200 kHz frequency. The ADCP was deployed at the sea floor to collect measurements at 2 meter intervals throughout the water column except for the extreme top and bottom. A Nortek Aquadopp, a high frequency acoustic Doppler current meter, was used to measure near-bottom water velocity. Near-bottom turbidity measurements were collected using an optical backscatter (OBS) sensor manufactured by D&A Instruments, Inc. Average tidal water level and burst surface wave measurements were collected using a Coastal Macrowave wave gauge. During synoptic boat-based surveys, an RD Instruments ADCP was utilized in reverse orientation (facing down) and mounted rigidly over the side of the vessel with the transducer face located below the water line. For navigation, the survey vessel was equipped with a Northstar 951X 12-channel Differential Global Positioning System (DGPS) unit (+/- 10 meters accuracy).

E.5 SPRING 2001 DATA COLLECTION PROGRAM RESULTS

The Spring 2001 data set is extensive with 10 bottom-based stations having recorded water velocity measurements at numerous depths, water level measurements, and turbidity measurements every 10 minutes for a two month period and a total of 41 boat-based water velocity measurement transits across sections of the study domain. Data processing and analyses were performed on the data to enhance its value in support of the LIS EIS. Data processing tasks included extensive quality assurance testing and formatting procedures to ensure high data quality and clear data presentation. Data analysis tasks focused on using the data to evaluate critically important characteristics relative to the LIS EIS including:

- *Assessment of potential for dredged material dispersion and transport during disposal events: water column hydrodynamics.* For this assessment, water velocities measured throughout the water column during the Spring 2001 program are presented. These data are important in assessing the potential for sediment transport during potential dredged material disposal events.
- *Assessment of potential for dredged material re-suspension and transport from the sea floor: near-bottom hydrodynamics.* To assess the potential for sediment re-suspension and transport away from the disposal site, (1) maximum near-bottom total water velocities were measured during the Spring 2001 Data Collection Program, (2) water velocity components were decomposed into tidal, high frequency, and subtidal components, and (3) the correlation of water velocities with wind events was evaluated.

E.5.1 Data Quality Assessment and Processing

Overall, the vast majority of data were successfully collected. A brief summary assessment of data quality is provided below:

- Water column water velocity data were successfully collected at all 10 monitoring locations by the ADCP and all ADCP datasets passed the data quality assurance evaluation.
- Near-bottom water velocity measurements, tidal height, and temperature from Nortek Aquadopp meters were successfully collected at 9 locations and data from these stations passed the data quality assurance evaluation. The meter at one station flooded during the deployment and therefore no data was obtained.
- Data from a total of 41 boat-based ADCP transits were successfully obtained along 21 transects. An error in the compass orientation required a correction that did not preclude data from passing the data quality assurance evaluation.
- Wave data were successfully collected at 2 of 3 stations; data from the 2 stations passed the data quality assurance evaluation.
- Turbidity measurements were successfully collected at 7 of 10 locations. Turbidity data required an offset correction and data at some of the stations is affected by biofouling toward the end of the deployment period, but the resulting data set passed the data quality assurance evaluation.

All datasets were downloaded from instruments using interface software and imported into MathWorks Matlab© for processing and analysis using a series of standard and customized routines. A Microsoft

Access97 relational database application was developed to store data collected during the Spring 2001 survey and historical studies. All datasets obtained during the Spring 2001 program were included in the database including hourly averages of near-bottom and water column currents, wave height, period and direction, water pressure, turbidity, and temperature. Water column currents measured during the synoptic survey transects were also included. The database also includes hourly averages of measurements collected during the previous NOS, SUNY, and City of New York studies.

E.5.2 Data Analysis and Interpretation

Analysis and interpretation of the Spring 2001 Data Collection Program data were performed to optimize the value of the data relative to supporting the LIS EIS.

Meteorological Data

The average daily air temperature was 5EC and temperatures ranged from –2EC to 11EC during the survey period. Air temperature trended slightly upward during the survey.

Winds were relatively calm through most of the survey period. Winds exceeding 10 m/s occurred at various times during the survey; these strong winds generally were not sustained for more than 8 to 12 consecutive hours. The longest sustained strong wind event recorded during the survey lasted for 106 hours (4.4 days). During that time, winds exceeded 10 m/s 74% of the time, winds exceeded 15 m/s for 10 hours, and the strongest wind speed (18.7 m/s) was recorded.

Tidal Height

Ranges in tidal height measured during the 2001 field program for each sub-basin are:

- Western LIS and Central LIS: typical tidal range ~ 2 m; neap and spring tide ranges ~ 1.5 m and 3 m
- Eastern LIS: typical tidal range ~ 1.5 m; neap and spring tide ranges ~ 1 m and 2.5 m
- BIS: typical tidal range ~ 0.75 m; neap and spring tide ranges ~ 0.5 m and 1.25 m

These data are typical of previously measured tidal data in the Sound.

Conductivity, Temperature and Depth Data

The temperature profiles measured by conductivity, temperature and depth (CTD) casts indicate that, at the beginning of the survey (March), there was minimal temperature stratification in LIS or BIS. Water temperatures ranged from 2EC - 3.5EC, with the higher temperatures in Eastern LIS and BIS. At the end of the survey, in mid-May, water temperatures warmed and the onset of stratification was evident. Water temperatures at the surface ranged from 9EC (in Eastern LIS and BIS) to 13EC (in Central LIS). In Western LIS and Central LIS, thermal stratification was fairly well developed, with surface temperatures 4ºC higher than temperatures deeper in the water column.

The salinity profiles show slight salinity stratification at all locations. During the deployment, salinities ranged from 27 ppt – 32 ppt, with the highest salinities observed in BIS. The maximum salinity gradient during deployment was ~1 ppt, observed in BIS. During retrieval in May, salinities were lower, ranging from 25 ppt – 31 ppt. Salinity gradients of ~1 ppt were observed in Western LIS, Central LIS and Eastern LIS. In BIS, the salinity gradient was ~3 ppt.

<u>Turbidity</u>

The turbidity measurements provide semi-quantitative estimates of turbidity at each sampling location. In general, turbidity measurements were relatively low (0 to 10 NTU) and contained modest tidal influences. Much of the turbidity data was noisy, with spikes of up to several hundred NTU, likely due to intermittent blocking of the sensor. Also, in several data sets, biofouling was observed toward the end of the survey.

In CLIS, background turbidity values of 0-3 NTU were measured and there was inconclusive evidence of correlation between wind events and increases in turbidity in the data record. In ELIS, a background turbidity of 2-4 NTU was observed, and higher measurements were not well correlated to higher bottom velocities. In BIS, background turbidity values of 4-5 NTU with a small (1-2 NTU) diurnal oscillation were measured, and small increases in turbidity were observed during wind events.

<u>Bottom Water Temperature</u>

Bottom water temperature rose from near 0ºC at the beginning of the survey to 8ºC to 12ºC at the completion of the survey. The highest water temperatures were recorded in Eastern LIS, the shallowest of the four basins. The maximum water temperature in Western LIS and BIS was 9ºC, and in Central LIS, 10ºC.

<u>Current Velocity</u>

The data collected in LIS and BIS support characterization of the magnitude and direction of water velocities throughout the study domain. In general, currents were observed to primarily follow a diurnal tidal cycle, with flow into the Sound (westward) on the flood tide. Currents decrease to near zero during slack tides as currents reverse, and water flows out of the Sound (eastward) on the ebb tide. Currents are predominantly in the east-west direction, and current magnitudes decrease with depth in the water column. The water velocities are highest in Eastern LIS, and decrease with westward distance into the

Sound. Both location and local bathymetry contribute to hydrodynamic variations within each basin and between basins.

Water Velocity Magnitude

In Western LIS, water velocity magnitudes at Station 02 were observed to be higher than those of Station 01 at surface and bottom, but lower at mid-depth. Also, there was a greater frequency of higher bottom currents at Station 02 than at Station 01. The maximum currents measured were:

- Surface: 65 cm/s and 111 cm/s, respectively at Stations 01 and 02.
- Mid-depth: 60 cm/s and 53 cm/s, respectively at Stations 01 and 02.
- Bottom: 34 cm/s and 44 cm/s, respectively at Stations 01 and 02.

In Central LIS, maximum water velocities at Stations 03 and 05 are generally higher than those at Station 04, and Station 05 has the greatest frequency of higher bottom water velocities. The maximum currents measured were:

- Surface: 91 cm/s, 76 cm/s, and 81 cm/s, respectively at Stations 03, 04 and 05.
- Mid-depth: 60 cm/s, 58 cm/s, and 58 cm/s, respectively at Stations 03, 04 and 05.
- Bottom: 33 cm/s, 27 cm/s and 44 cm/s, respectively at Stations 03, 04 and 05.

In Eastern LIS, water velocity magnitudes at Stations 06 and 07 were similar, although Station 06 generally had slightly higher values. There is a greater frequency of higher bottom currents at Station 08 than at Station 06. The maximum currents measured were:

- Surface: 136 cm/s, 125 cm/s, and 85 cm/s, respectively at Stations 06, 07 and 08.
- Mid-depth: 101 cm/s, 106 cm/s, and 87 cm/s, respectively at Stations 06, 07 and 08.
- Bottom: 52 cm/s and 60 cm/s, respectively at Stations 06 and 08.

In BIS, maximum surface and bottom water velocities were greater at Station 09, and maximum water velocities at mid-depth were greater at Station 10. There was greater frequency of higher bottom currents at Station 09 than at Station 10. The maximum currents measured were:

- Surface: 157 cm/s and 125 cm/s, respectively at Stations 09 and 10.
- Mid-depth: 91 cm/s and 95 cm/s, respectively at Stations 09 and 10.
- Bottom: 60 cm/s and 39 cm/s, respectively at Stations 09 and 10.

Water Velocity Direction

The currents throughout the Sound were generally oriented east-west, reversing twice daily with the tides. In Western LIS, and to a lesser extent in Central LIS, the direction of the current rotated slightly with depth. In Eastern LIS and BIS, the current direction was coincident at all depths in the water column. In BIS, the direction of the surface current was more variable than in other locations.

Tides were observed to be generally asymmetric, meaning that the duration and peak current speed of the flood and ebb tide were not equal. Western LIS and Central LIS stations were typically flood dominant, with flood tide speeds about 1-3 cm/s greater than those of ebb. In addition, the duration of ebb was about 10-40 minutes longer than the duration of flood tide. The exception was Station 01, where tides were slightly ebb dominant. Stations in Eastern LIS and BIS were typically ebb dominant, with ebb speeds 1-5 cm/s greater than flood currents. The exception was Station 07, which was strongly flood dominant.

Water Velocity Decomposition

Total water velocity data were decomposed into component tidal, high frequency (generally associated with noise) and subtidal velocities to support evaluation of potential maximum water velocity conditions. Two methods of analyzing the decomposed velocity data were applied: tidal ellipse development and harmonic analysis.

Tidal ellipses display the magnitude, phase and direction of the M_2 tide, the dominant tidal constituent. The M_2 amplitudes were greatest at stations near The Race in Eastern LIS and BIS, decreasing in Central LIS, and weakest in Western LIS and areas removed from the main axis of the basin (Station 04). In general, the ellipses for surface and mid-depth are narrow for all locations, indicating that flow was primarily in the dominant east-west flow direction. At Stations 01, 04 and 10, the ellipses at the lower depths are wider, indicating some flow normal to the dominant flow direction at these depths. At Station 06, all of the ellipses are narrow and aligned in the same direction, indicating that flow at all depths is in the same direction at the same time.

Harmonic analysis results in presentation of the decomposition of currents into tidal, high frequency and subtidal constituent currents and the energy in each of the decomposed current constituents. At the surface, the percentage of total energy in the tidal signal ranged from 36% to 94%. The high frequency signal comprised 4% to 39% of the total energy, and the sub-tidal comprised of 1% to 45%. In BIS, sub-tidal energy comprised the most significant portion of the total energy (28% to 45%). At middle and bottom depths, the tidal energy comprised at least 70% of the total energy at all locations, and the sub-tidal energy was less than 7%. These results suggest that the tidal component generally comprises the majority of the total current velocity but that the high frequency and sub-tidal components can significantly influence instantaneous peak velocities.

Wind Events

The wind data record concurrent with the Spring 2001 Data Collection Program was reviewed and two relatively high wind events were selected and analyzed to enhance understanding of the wind-driven component of total water velocity in support evaluation of maximum total water velocity conditions. Wind Event #1 (March 20 to March 24, 2001) had high winds (greater than 10 m/s for 74% of the event) for 106 hours out of the east. Wind Event #2 (May 1 to May 5, 2001) had sustained moderate wind speeds (8-10 m/s) out of the southwest.

During Wind Event #1, the surface water velocity magnitude was observed to increase in response to the wind forcing in Western LIS, Eastern LIS, and BIS. Water velocity magnitudes at deeper locations did not respond noticeably to the wind. In Central LIS, there was a minimal noticeable response of water velocities at all depths.

During Wind Event #2, there was an increase in surface water velocities but no effect on velocities at depth in response to the wind forcing in Western LIS and Eastern LIS. Water velocity magnitudes at deeper locations did not respond noticeably to the wind. In Central LIS and BIS, there was little effect of wind forcing on water velocity at any depth.

Boat-based ADCP Transects

The boat-based ADCP survey featured measurement of water velocities throughout the water column across large cross-sectional expanses (e.g., several miles each) of the study area along 21 transects. In general, the results show good correlation with data measured at the 10 fixed stations. The velocity distributions throughout most of the transect cross-sections show little bi-directional flow (i.e., throughout the cross-section most of the flow was in the same direction). Where bi-directional flow was observed, velocities were generally small, and flow in opposite directions was limited to the edges of the transects.

Waves

Wave burst data were recovered at two stations, Station 01 (Western LIS) and Station 04 (Central LIS). A spectral analysis of the wave burst data was conducted to determine the significant wave height (H_s, average of the top 1/3 waves), peak period (T_p) and wave direction (D_p). In general, the highest wave peaks and high bottom orbital velocities corresponded with the higher winds, and the wave direction corresponds to the wind direction.

Significant wave heights of 1.3 m to 2 m and peak periods of 4 to 6 seconds were observed during the 2 strongest wind events. The bottom orbital velocities during these events were 1.7 – 2 cm/s at Station 01 (in 31 m of water) and 4.5 – 7 cm/s at Station 04 (in 19 m of water). These results are consistent with those of previous model predictions.

E.6 CONCLUSION

The Spring 2001 Data Collection Program was designed to capture maximum energy or "worst-case" hydrodynamic conditions at numerous locations concurrently throughout the study area in order to provide data necessary to assess the potential for dredged material transport (1) during disposal events and (2) via re-suspension from the sea floor following dredged material disposal. The following observations may be made based on Spring 2001 data set:

- Maximum water column water velocity magnitudes were observed near the water surface and ranged from 65 cm/s in Western LIS to 157 cm/s in BIS.
- Maximum near-bottom (1 meter above sea floor) water velocity magnitudes were observed to range from 34 cm/s in Western LIS to 60 cm/s in BIS.
- Previous general characterizations of spatial variations in currents were confirmed. Currents generally weakest in Western LIS and increased with distance east.
- Significant variability in water velocity characteristics was observed within each basin.

In Western LIS, the mean near-bottom water velocity was less than 10 cm/s and measurements greater than 20 cm/s were relatively infrequent (less than 5% of measurements). In Central LIS, the mean near-bottom water velocity was approximately 12 cm/s and measurements greater than 20 cm/s were relatively infrequent (less than 10%), except at Station 05 located toward the eastern end of Central LIS. In Eastern LIS, the mean near-bottom water velocity measurement was approximately 18 cm/s with relatively frequent measurements greater than 30 cm/s (~10%). In BIS, the mean near-bottom water velocity measurement was approximately 18 cm/s, with values greater than 30 cm/s relatively frequent (~18%) at Station 09 but relatively rare (~2%) at Station 10.

An analysis of each of the major components of water velocities (i.e., decomposition analysis) measured during the Spring 2001 Data Collection Program was conducted to optimize the value of the data. The water velocity decomposition analysis was conducted to support determination of maximum potential total water velocity conditions. The following observations were made based on this analysis:

- Tidal currents generally dominate the total current regime, representing an average of 85% of total energy.

- Although non-tidal currents account for only an average of 15% of total energy, they are critically important to evaluation of maximum current conditions.
- At specific times, other water velocity components, such as wind-driven and waves-driven components, can approach the magnitude of tidal current components and may combine to result in maximum or worst-case current conditions.
- If peak water velocity components had occurred simultaneously, the maximum total near-bottom water velocity measurements would have been 10 to 20 cm/s larger than actual measured values.

Using the Spring 2001 data set, water column water velocity measurements can be used to evaluate the potential for dredged material transport using available mathematical models. Assessment of the potential for dredged material re-suspension and transport may be performed using near-bottom water velocity measurements along with additional information.

Application of the physical oceanographic data to support the EIS evaluation will likely require additional evaluation, including:

- Mathematical modeling of hydrodynamics throughout the entire study domain to enhance understanding of spatial variability in currents, particularly bottom currents during storm events with different wind conditions than those that occurred during this program.
- Mathematical modeling to predict the potential for dispersion and transport of dredged material during disposal events.
- Site-specific assessment of the potential for sediment re-suspension including the evaluation of bottom shear stresses, sediment characteristics, and hydrodynamics at selected locations.

The physical oceanographic evaluation of LIS and BIS has provided a technically strong data set to support the EIS for dredged material disposal.

1.0 INTRODUCTION

The purpose of this report is to document the physical oceanographic characteristics of Long Island Sound (LIS) and Block Island Sound (BIS) in support of the Long Island Sound Environmental Impact Statement (EIS). Physical oceanographic characteristics include water circulation patterns, water velocity dynamics, tidal water level dynamics and sediment transport. These characteristics have been evaluated throughout LIS and BIS with the focus on factors affecting potential dredged material disposal process. This report provides a summary of physical oceanographic characteristics throughout the study area and is designed to support evaluation of regions within the study domain for potential dredged material disposal site designation from a physical oceanographic perspective. As the EIS process proceeds, these characteristics will be evaluated along with others, including those focused on ecological and socio-economic factors.

Information on physical oceanographic characteristics were obtained through evaluation of existing literature and existing data, and through performance of a major field data collection program in the Spring of 2001. Quantification of water column and near-bottom water velocities and the factors leading to maximum near-bottom water velocities were focus areas of the Spring 2001 study. The time frame for the study period was selected based on the potential for “worst-case” storm conditions and associated maximum water velocities to occur.

This section provides an overview of the regulatory and technical context for the physical oceanographic information presented in this report. The purpose, scope, and organization of this report will also be described.

1.1 BACKGROUND

1.1.1 <u>The Environmental Impact Statement (EIS) Process</u>

The U.S. Environmental Protection Agency, Regions I and II (USEPA, Regions I and II), and U.S. Army Corps of Engineers, New England District (USACE or the Corps), are proceeding with the preparation of an Environmental Impact Statement in compliance with the National Environmental Policy Act (NEPA). The EIS will consider the potential designation of one or more dredged material disposal sites in the waters of LIS and BIS consistent with the provisions of Section 102 (c) of the Marine Protection, Research, and Sanctuaries Act (MPRSA) and 40 CFR 230.80 of USEPA’s regulations under Section 404 of the Clean Water Act (CWA).

The open water component of the EIS process may be described as a series of the following three evaluation phases:

1. *Siting feasibility analysis.* Data will be collected and used to assist in determining the feasibility of locating disposal sites anywhere in LIS and/or BIS. If specific regions of the study area pass the siting feasibility analysis criteria, then the next evaluation phase will be performed.

2. *Site-screening.* The site-screening process requires characterization of the study area in terms of several critical factors including hydrodynamics, potential for ecological impact, and economics. Once characterized, each critical factor would be represented as a map overlay with contours indicating degrees of suitability for disposal sites throughout the study area (i.e., a spatial ranking system). The completed map will present the study area (i.e., LIS and BIS) with a spatial ranking of disposal site acceptability for each critical factor. Review and consideration of the spatial ranking map would support selection of appropriate alternative disposal sites.

3. Site-specific alternative disposal site evaluation. This evaluation will be performed at each site selected during the site-screening process. Site-specific evaluations should feature collection of detailed data to support potential site designation. Site-specific hydrodynamic data collection must be sufficient to support required evaluations, such as computer modeling, to assess the potential for dredged material transport from each alternative site.

In order for sites within the study area to be designated for dredged material disposal, they must be evaluated using the appropriate data from the physical oceanographic characterization and other data collection efforts for each of the three phases described above.

1.1.2 The Role of Physical Oceanographic Characterization in the EIS Process

Physical oceanographic characterization is an important component of the EIS process because the extent of dredged material transport in the open water environment is dependent on hydrodynamics. Specifically, ambient water currents can transport dredged material suspended in the water column during disposal events and can re-suspend and transport dredged material from the seafloor via scouring following disposal events. Because of the importance of the physical oceanographic characteristics of a site with respect to the potential for dredged material transport, specific regulatory criteria exist for assessing potential disposal sites as described below.

Prior to making a decision on designation of a disposal site, the USEPA is required to evaluate the environmental and socioeconomic impacts of a range of alternatives for disposal of dredged material in the waters of LIS and BIS. Federal regulations specify the set of criteria to use in making these evaluations (40 CFR Section 228.4(e), 228.5, and 228.6). These criteria include evaluation of physical, chemical, and biological characteristics, existing uses, and existing regulations at the site. In terms of hydrodynamic characteristics, the criteria specify that designated sites should be evaluated for transport of dredged material away from the disposal site and for impacts on the adjacent resource areas (e.g., fisheries and shorelines). Evaluation of the potential for "dispersal, horizontal transport and vertical mixing characteristics of the area, including prevailing current direction and velocity, if any" (CFR Section 228.6 specific criteria #7) is specifically required as part of the site assessment process. Assessment of near-bottom currents is of critical importance in evaluation of potential disposal sites due to the potential adverse effects of re-suspension and transport of dredged material from the seafloor. This report is intended to contribute to the EIS for designation of disposal sites in LIS and BIS by providing hydrodynamic information required to support the evaluation process specified in Federal regulations.

1.2 PREVIOUS PHYSICAL OCEANOGRAPHIC STUDIES OF LONG ISLAND AND BLOCK ISLAND SOUNDS

Previous studies of LIS and BIS physical oceanography provide the starting point for collection of the hydrodynamic information needed to support the EIS. The first task in preparing this report was to review the physical oceanographic literature concerning Long Island and Block Island Sounds and to identify and acquire previously existing hydrodynamic data sets. Section 2 of this report summarizes the results of the literature review while Section 3 describes the hydrodynamic data sets obtained for previous measurements in LIS and BIS. Analysis of these historical data sets is also presented in Section 3. The historical data are provided in an electronic database (Electronic Attachment 2) and reproduced in Electronic Attachment 5, Long Island Sound/Block Island Sound Historic Physical Oceanographic Data (Unprocessed).

For LIS and BIS, water velocity data, as well as data on depth, water level, tide height, temperature, and conductivity were obtained from three studies (not all parameters recorded in all studies):

- The Long Island Sound Oceanography Project conducted by the National Ocean Service (1988-1990);
- The Long Island Sound Study conducted by the Marine Sciences Research Center of the State University of New York (1988); and,
- Data collection programs in the New York Bight, New York Harbor, and Long Island Sound sponsored by the City of New York and conducted by Battelle Ocean Sciences (1994-1995).

The Long Island Sound Oceanography Project included two stations in BIS. The other two studies collected data only in LIS. Review of the existing studies and data sets identified the following areas in which additional data was required to support the EIS:

- Little data collection activities focused on measurement of hydrodynamic conditions during storm events in the Sound. Storm conditions have the potential to enhance sediment re-suspension by strengthening bottom-water velocities.

- Little wave data were collected along with current measurements. Wave data are important in that it enables investigators to explore the effects of wave energy on near-bottom (and potentially, water-column) water velocities. Water velocities affect the potential for sediment re-suspension.

- Little data were collected concurrently at different locations to support spatial characterization and comparison of hydrodynamic conditions.

- Little data were generally collected in the Central LIS basin and in BIS. A better characterization of the hydrodynamics of these areas is needed to support the EIS.

The review of existing information was applied to support design of the Spring 2001 Data Collection Program.

1.3 PURPOSE AND SCOPE OF THE SPRING 2001 DATA COLLECTION PROGRAM

The objective of the hydrodynamic field data collection program was to fill the data gaps outlined above and provide the data required to support the EIS evaluation. Field measurement data from the program will be used to evaluate siting feasibility and site-screening by comparing specific hydrodynamic measurements (e.g., near-bottom water velocities) to criteria established for acceptability in terms of disposal sites characteristics (e.g., maximum acceptable near-bottom velocities). For site-screening, collected measurements from the program will be used for developing a spatial suitability ranking contour map of the entire study area. Site-specific data characterization of alternative disposal sites will provide data required to support site-specific dredged material transport assessment and modeling as part of an evaluation of the potential for transport of dredged materials during disposal events and from the sea-floor via worst-case scouring events.

The hydrodynamic field program was designed to capture worst-case hydrodynamic conditions at numerous locations throughout the study area, consisting of LIS and BIS. Worst-case conditions are generally associated with maximum storm and wind energy scenarios, conditions known to occur most frequently during the spring and fall months. Thus, the Spring 2001 field program was performed during a period with maximum potential for capturing hydrodynamics in the study area under worst-case conditions.

The field program consisted of the following two major components: (1) the deployment of bottom-based, state-of-the-science instrument suites to measure hydrodynamics continuously for a period of two months at 10 selected locations and (2) a synoptic, boat-based survey performed to compliment long-term data collection by providing spatial characterization at selected times. Instrument suites deployed on the sea-floor contained an acoustic Doppler current profiler (ADCP), a near-bottom current meter, a tide gauge, and a turbidity sensor. Station locations for these instrument suites included Western LIS, Central LIS, Eastern LIS, and BIS. Multiple stations were located in each of these basins or study regions in order to provide data to evaluate the hydrodynamic spatial variability in the four study regions.

In order to provide detailed data on spatial variability in the study regions, synoptic current measurements were collected using a boat-based ADCP. The boat-based ADCP was deployed over the side of a vessel and measured water velocities throughout the water column as the vessel transited pre-selected transects. This sampling approach provided detailed water velocity characterizations at specific “snapshots” in time (e.g., during flood and ebb tides).

1.4 REPORT ORGANIZATION

The remainder of this report is organized as follows:

- Section 2 provides a characterization of the physical oceanography of LIS and BIS based on previously existing information;
- Section 3 discusses previous physical oceanographic studies of LIS and BIS and provides a summary analysis of the data;
- Section 4 describes the objectives, procedures, and methods used in the Spring 2001 Data Collection Program;
- Section 5 provides a description of the data processing procedures, and an analysis and interpretation of the data from the Spring 2001 Data Collection Program; and
- Section 6 provides a concluding summary of the results of the Spring 2001 Data Collection and a reassessment of the hydrodynamic characterization of LIS and BIS based on the Data Collection Program results.

Accompanying the main text of this report are two appendices. The contents of these appendices are described below:

- Appendix A contains a supplemental document entitled “Specification of a Worst-Case Storm Event in Long Island/Block Island Sound”. Excerpts from this report are discussed in Section 2.
- Appendix B contains a supplemental document entitled “Hydrodynamic Circulation of Block Island Sound: Literature Review and Analysis”. Excerpts from this report are also discussed in Section 2.

Six electronic attachments have been prepared to supplement the printed material in this report. These electronic attachments may be found on the compact disks accompanying this text. Each electronic attachment includes a guide describing the content and form, and providing instructions for use of the electronic attachment. The contents of the electronic attachments are described below:

- Electronic Attachment 1 contains a pdf version of this report.
- Electronic Attachment 2 contains an electronic database containing physical oceanographic data collected in LIS and BIS during historic field studies and during ENSR's Spring 2001 Data Collection Program.
- Electronic Attachment 3 contains an interactive map showing the locations of historic and Spring 2001 field data collection programs in LIS and BIS. The locations of historic disposal sites in the Sound are also shown.
- Electronic Attachment 4 contains a complete set of figures depicting the data and analysis of the data collected during ENSR's Spring 2001 Data Collection Program and during the National Ocean Service's 1988-1990 field program. A subset of these figures are reproduced in Sections 3 and 5 of this report.
- Electronic Attachment 5 contains the unprocessed data collected during historic physical oceanographic field programs in LIS and BIS.
- Electronic Attachment 6 contains the unprocessed data obtained during ENSR's Spring 2001 Data Collection Program.

2.0 HISTORIC CHARACTERIZATION OF HYDRODYNAMICS, SEDIMENTS, AND STORM EVENTS IN LONG ISLAND SOUND AND BLOCK ISLAND SOUND

This section summarizes the information available in the literature concerning the hydrodynamics and sediment characteristics of LIS and BIS. In addition, a summary of historic meteorologic data with interpretation and identification of potential "worst-case" conditions in terms of potential for dredged material transport is provided. A more detailed summary of the historic worst-case storm evaluation is attached in Appendix A.

2.1 LONG ISLAND SOUND

A brief overview of LIS hydrodynamics, sediment composition, and sediment transport is provided below.

2.1.1 Hydrodynamics

The hydrodynamics of LIS have been studied through collection and analysis of field data and through mathematical modeling applications. Characterization of the currents and circulation patterns in the Sound has provided an understanding of Sound-wide hydrodynamics and the observed sedimentary environments. General characteristics and previous hydrodynamic studies within the Sound are briefly summarized below.

Long Island Sound is approximately 90 miles long and 15 miles wide and oriented along a roughly east-west axis with open ocean exchange at eastern and western boundaries (Figure 2-1). The mean depth of the Sound is 20 meters and the maximum depth is 90 meters near its easterly boundary (Wolfe et al. 1991). The bathymetric map of the Sound (Figure 2-1) was compiled from National Ocean Survey (NOS) Hydrographic surveys, USGS bathymetric surveys, and National Oceanic and Atmospheric Administration (NOAA) nautical charts.

Water movement in LIS is primarily driven by tidal forcings, with wind, storm events and freshwater inflows contributing to varying degrees. Storm events, producing wind-waves and establishing energetic flow regimes, combine with normal tidal forcings to create maximum water velocities and "worst-case" conditions in terms of potential dispersion of dredged material. Specifically, sustained storm events (e.g., 48 hours) featuring high winds along the axis of the Sound (i.e., roughly east-west) are expected to produce maximum bottom currents and potentially result in maximum sediment re-suspension in the Sound.

Water velocity magnitudes have been observed to be greatest in Eastern LIS and generally diminish with distance west. The amplitude of the M_2 tide, the dominant tidal constituent, increases by a factor of 3 between the east and west end of the Sound, with similar decreases in water velocity indicating that the Sound is a resonant basin (Gordon 1980). Tidal currents are generally oriented along the east-west axis of the Sound.

Although LIS is not a typical estuary, with a river at the upstream end, well-developed estuarine circulation has been observed. In general, fresher, less dense water flows eastward along the surface, while saline water flows westward along the bottom of the Sound. There is a general counter-clockwise circulation in LIS, with currents along the north shore heading to the west and currents along the south shore heading east. There is also evidence for several localized gyres within the body of the Sound (Welsh 1992).

Schmalz (1993) applied a three-dimensional hydrodynamic model to decompose the residual circulation into individual forcing components. He examined the relative effects of astronomical tide, density-driven currents, local wind driven currents and non-local shelf wind driven currents on the residual circulation patterns. Model simulations revealed the presence of counterclockwise gyres in the Western LIS and Central LIS basin, set up by the astronomical tide alone, and enhanced by the gravitational forcing due to density gradients. Near the surface of the water column, Schmalz found that forcing due to astronomical tide, density gradients and local wind were of the same order of magnitude, while the contribution of non-local shelf winds was an order of magnitude lower. Near the bottom of the water column, astronomical and density-driven forcings were slightly higher than local wind forcings, and non-local shelf winds had no effect on the predicted residual currents.

The U.S. Geological Survey (USGS) set up a three-dimensional hydrodynamic model to predict bottom currents and to characterize the sedimentary environment of the Sound (Signell et al. 1997). The model included tidal and local wind forcings and assumed uniform water density. The model predicted bottom currents 1 meter above the sea floor throughout LIS (see Figure 2-2), excluding a large portion of Eastern LIS. The model predicted tidally-driven bottom currents of less than 20 cm/s in the Western LIS, between 20-40 cm/s in the Central LIS, 30-60 cm/s in a portion of the eastern Sound, and greater than 50 cm/s in the constriction at the eastern end of the Sound. Areas where the model predicted bottom tidal currents greater than 30 cm/s corresponded to regions identified as erosional or non-depositional. In a further study, Signell et al. (2000) applied a model to evaluate the effect of wind on waves and associated bottom orbital velocities that could induce sediment transport. It was determined that wind-generated waves likely generate bottom orbital velocities greater than 15 cm/s in near-shore regions, which could induce sediment transport. Offshore, at water depths greater than 20 m, there is little potential for wave induced bottom orbital velocities that could cause sediment transport.

Vieira (2000) analyzed a series of velocity measurements to examine the long-term, residual circulation in the Sound. By filtering and averaging each data set, Vieira was able to describe residual flow patterns resulting from tidal and gravitational forcing, independent of time or specific events. Vieira observed denser, saline water entering the Sound from the east and flowing underneath outgoing, less saline water, indicative of classic estuarine circulation. In the Central BIS, he observed the incoming, saline water flowing through the deep, southern part of the sound, and the outgoing water flowing above it at lower speeds. In Western LIS, outgoing flow is generally along the southern shore of the sound, and in the upper part of the water column, as the estuarine circulation is established. A counterclockwise gyre is discernable in Western LIS, consistent with the modeling results of Schmalz.

Kaputa and Olsen (2000) conducted a review of seven years of water quality data, primarily to understand the spatial and seasonal patterns of hypoxia in LIS. Time series measurements of temperature and salinity indicated a density stratification in the water column. The data revealed a strong temperature gradient, with warmer water above cooler bottom water. The temperature gradient was largest during June and early July, likely driven by warming air temperatures. Salinity gradients have also been observed, when saline water flows below fresher water, as previously described. These vertical density gradients lead to stratification in the water column, which contribute to the observed flow patterns in the Sound.

2.1.2 Sedimentary Environment

Knowledge of the surficial sediment distribution can provide an understanding of the bottom current climate. Areas of stronger bottom currents may be composed primarily of larger-sized sediments; conversely, areas featuring finer-grained sediments such as mud and silt could be considered to lie within milder current regimes. The bottom sedimentary environment of LIS has been characterized by the USGS, in cooperation with the Connecticut Department of Environmental Protection and the USEPA (Knebel 1998). The sedimentary environment is indicative of the movement and deposition of sediments in the Sound due to local and regional geologic and oceanographic conditions (Figure 2-3, Poppe et al. 2000).

To characterize the sedimentary environment of LIS, the USGS conducted an extensive survey of the sea floor. Sidescan sonographs were collected and analyzed with the aid of sediment grab samples and video camera observations. A map of surficial sediments (0-2 cm below the seabed) was created from samples and photographs at 1,643 locations within LIS combined with almost 13,000 published textural descriptions. As shown in Figure 2-4, four long-term sedimentary environments were identified: erosion or non-deposition; coarse-grained bedload transport; sediment sorting and reworking; and fine-grained deposition. This figure provides an understanding of the regional processes that distribute sediments and associated contaminants (Knebel and Poppe 2000).

At the eastern edge of the Sound, extending approximately 5 to 8 km west, there is a large area of erosion or non-deposition, likely caused by a combination of strong tidal currents and a net westward movement of sediments into the estuary (Knebel 1998). West of this region is an area of coarse-grained bedload transport. This region extends approximately from the mouth of the Connecticut River westward 15 km, and is bordered on the western edge by a 5-km band of sediment sorting and reworking. The seafloor in this region is primarily sand, and transitions gradually to marine mud towards the central basin. The central and western basins of the Sound are predominantly regions of fine-grained deposition. In localized areas, generally along north-south oriented shoals, there are regions of erosion or non-deposition and sediment sorting and reworking.

Turbidity measurements indicate that waves influence sediment transport around the margin of the Sound, up to depths of approximately 18 m (Bokuniewicz and Gordon 1980a). Within this margin, the bottom sediments are primarily sand, transitioning to mud with greater depths. In these deeper regions of the Sound, waves are expected to have little influence on sediments.

The primary source of sediment entering LIS is river inflow. Sediment loading from rivers varies greatly, with the majority being delivered during periods of storms and subsequent high discharge. Estimates of the load contributed by the Connecticut River (which contributes 71% of the total freshwater inflow) range from 0.8 x 10^8 kg/yr to 5 x 10^8 kg/yr (Bokuniewicz and Gordon 1980a). In general, sediment loading from rivers into the Sound is less than that of other estuaries, due to the erosion resistance of the glacial terrain that covers much of central New England (Gordon 1980). Other sources of sediment include shoreline erosion and exchange with the continental shelf, both of which have not been well quantified, but are considered to contribute less than river inflow. Estimates of sediment supply into the Sound and sedimentation within the Sound are nearly equal, suggesting that the trapping efficiency of the Sound is nearly 100% (Gordon 1980).

Sand transport (particle size >70µm) covers approximately 44% of the floor of the Sound (Bokuniewicz 1980). As mentioned above, the eastern portion of the Sound floor is covered by sand, transitioning westward to mud. The eastern edge of this transition zone is a north-south sand ridge called Mattituck Sill. The Sill is covered with sand waves, and sand movement occurs primarily as bedload transport. A net westward flux of sand has been calculated in this region, attributed to the superposition of the estuarine current on the tidal currents (Bokuniewicz 1980). As the sand moves westward, it is immobilized by incorporation into the mud deposits that cover the central and western regions of the Sound.

The silt and clay particles that enter the sound are rapidly processed by benthic animals, which produce aggregate pellets (100 – 500µm). The lack of individual particles with the Sound indicate that the rate of pellet production by the benthic community is large compared to the rate of sediment supply (Bokuniewicz and Gordon 1980a). A 10 mm layer of these pellets blanket the mud-dominated portions of the sea floor throughout the Sound. This layer can be re-suspended into the water column due to tidal excitation and storm events. Only during the largest storm events is the entire layer re-suspended. At the bottom of this layer, the pellets are converted into cohesive sediments, and are no longer subject to re-suspension.

This mud, or permanent sediment, is estimated to accumulate at an approximate rate of 1 mm/yr. The production of new pellets maintains the approximately constant thickness of the upper, mobile layer of particles.

The potential for re-suspension of sediment by waves generated by local winds was evaluated through simulated patterns of wave orbital currents. A threshold orbital velocity of approximately 15 cm/s was estimated as being required to suspend fine-grained muds (Komar and Miller 1975). In water depths greater than 20 m, this threshold value was exceeded less than 0.001 percent of the time, based on simulations using 12 years of wind data (Signell et al. 2000). Numerical models simulations for tide, density, wind and wave driven bottom currents may be related to the observed seafloor characteristics.

2.2 BLOCK ISLAND SOUND

A brief overview of BIS hydrodynamic and sediment characteristics is provided below. A more detailed report on BIS hydrodynamics is attached as Appendix B. In general, fewer physical oceanographic studies of BIS have been performed than for LIS. The following description of circulation provides an overview of the dominant patterns and physical processes in BIS.

2.2.1 Hydrodynamics

Block Island Sound is a semi-enclosed water body situated south of Rhode Island and east of Long Island, NY (Figure 2-5). BIS is separated from the New York Bight to the south, Rhode Island Sound to the east, and LIS to the west. Block Island Sound is connected to Long Island Sound via a channel known as The Race (Figure 2-6). The Race is a deep, relatively narrow passage featuring highly-variable bathymetry. Its deepest portions are about 60 meters. The shallow portions form a sill between the basins of LIS and BIS. Plum Gut, located adjacent to The Race between Plum Island and Orient Point, Long Island, is another major exchange channel with LIS. Block Island Channel is located between Southwest Ledge (southwest of Block Island) and Endeavor Shoals off Montauk Point. Block Island Channel also exhibits variable bathymetry, with the sill depth on the order of 30-37 m. Southwest Ledge is in the order of 12-18 m deep, and comprised of boulders and gravel. Endeavor Shoals are 9-12 m deep, and possess large sand waves fanning radially around Montauk Point (Yokubaitis 1977). A wide passage between Block Island and Point Judith separates BIS from Rhode Island Sound. This passage is relatively wide, measuring approximately 8.5 nautical miles across, and lacks the defined sill of the western channels. This passage features more gradual bathymetric slopes with maximum depths on the order of 45 m, however the bottom slopes steeply from Sandy Point, Block Island to the main channel with a milder slope from the main channel to Point Judith.

The bathymetric ridges, especially Endeavor Shoals and Southwest Ledge, protect BIS from open-ocean swell from the Atlantic Ocean. Much of the Sound is in the lee of this moraine feature, sheltered from significant storm wave energy generated offshore. Eastern areas of BIS are open to unlimited fetch to the east and south. The Block Island land mass provides an important barrier to water transport and ocean waves, creating sheltered regions where conditions are relatively mild.

Flood tides flow into BIS through the two main passages (Rhode Island Sound passage and Block Island Channel), and form a progressive wave, which becomes a standing wave at the entrance to LIS (Redfield 1950). The M_2 tidal wave arrives initially through the eastern passage to Block Island, and a short time later through Block Island Channel. Flood currents are westerly through the Rhode Island Sound passage, and northwesterly through Block Island Channel and adjacent shoals (Figure 2-7). Currents converge within the Sound and flood through The Race with considerable strength. The strongest flood currents are located within the deeper channels and around headlands such as Montauk Point, Point Judith, and Sandy Point. Weaker currents have been observed in the eastern-central portion of the Sound, where Block Island creates a lee from the flooding tidal wave.

The tide reverses during the ebb, and flows nearly in the opposite direction at all locations (Figure 2-8). Ebb flow through BIS separates into two main branches: one branch exiting southeasterly through Block Island Channel and the other easterly through the Rhode Island Sound passage. The dominant branch is through Block Island Channel and across adjacent shoals. Tidal current charts show that ebb flow currents through Block Island Channel are two-to-three times faster than currents through the Rhode Island Sound passage.

Residual drift in BIS has been studied via drifter, or drogue, studies and through processing of water velocity data. Results describe a two-layer estuarine system, with the upper surface responding strongly to wind stress, and the lower layer correlated more strongly to tidal asymmetry. In general, the upper layer showed a net eastward drift, exiting BIS, consistent with prevailing winds from the southwest (in spring and summer) and the northwest (in winter). The lower layer (near bottom) showed a net westward drift, into the estuary. Surface current observations have also shown evidence of a large-scale transient eddy, as shown on Figure 2-9 (NOPP/CODAR 2001).

2.2.2 Sedimentary Environment

Sand is the most dominant textural class within BIS (Figure 2-10), covering most of western and central regions (Savard 1966). The greatest concentration of silt and clay was found in Napeague Bay and areas in the submerged central plain west of Block Island. These regions have been identified as having the weakest observed currents. Samples containing gravel were found on Southwest Ledge, the shoal northeast of Montauk Point, Block Island Channel, and The Race. Gravel was also found in patches in the passage between Rhode Island and Block Island Sounds. These regions were observed to have the swiftest currents.

Fine-grained and very fine-grained sediments were found in the central area of BIS, with mean grain size increasing with distance from the center (Savard 1966). Nearly half of the samples had grain sizes between fine sand (125-250 µm) to coarse silt (34-62 µm). Samples with the highest concentration of silt/clay (above 25%) were located west-northwest of Block Island. South of Rhode Island, small amounts of silt were found at depths greater than 27 m (Figure 2-10).

2.3 REVIEW OF THE METEOROLOGICAL RECORD TO IDENTIFY WORST-CASE STORMS

The information collected to date indicates that wind-driven bottom flow in Long Island and Block Island Sounds is much weaker than tidal currents. However, sustained strong-winds could provide additional energy that, when combined with tidal or density-induced currents, exceeds the energy threshold for re-suspension and transport of sediments. As a first step to assessing the impact of storm events on sediment transport in Long Island and Block Island Sounds, the historical wind data was analyzed to identify "worst-case" storms. Worst-case storms, in this context, denote storms with the greatest potential to enhance sediment transport. A report detailing the methodology used to identify worst-case storms, the results of that analysis, and the implications of these results for sediment transport is contained in Appendix A of this report. Information from Appendix A regarding identification of worst-case storm events from the historical record is summarized below.

2.3.1 Methodology

Historical wind speed and direction data in Long Island and Block Island Sounds were obtained from three land-based monitoring stations (Brookhaven National Laboratory; Groton Connecticut Airport; Block Island, RI) and one sea-based monitoring station (the National Oceanic and Atmospheric Administration (NOAA) C-Man buoy BUZM3 located in Buzzards Bay, Massachusetts) (Figure 2-12). Data from at least one station was available for the years 1943, 1951-54, 1960-2001. In most cases, data obtained from the NOAA BUZM3 were deemed most valuable. This sea-based station was less affected by frictional terrain attenuation of wind speeds than were land-based stations and data obtained from this station are thought to be more representative of actual wind stress applied to the sea surface of the study area. Data from the other locations were used to verify and supplement storm wind magnitude/direction at the Buzzards Bay C-Man buoy. When data from Buzzards Bay were not available (pre-1985), wind data from other locations were used.

A logical screening procedure was developed to evaluate worst-case storms. For many of the field survey monitoring stations, strong winds from the west appear to impact bottom currents most significantly. Other sites, such as those in Eastern LIS, may also be impacted by south winds, and in BIS, by winds from the east. Because of this directional spread, three cases were developed in this evaluation procedure: storms from the west, south, and east. For each case, one or several "typical" storms were identified from the historical wind records and presented.

Historical data was screened according to the following criteria:

1. Average wind speeds greater than 15 m/s in the principal direction (roughly west, south, or east) for the land-based stations and 20 m/s for the sea-based station were included; all other winds were discarded as being unlikely to influence wave-generated bottom currents. All data points exceeding this threshold were retained with their associated time/date and analyzed in more detail.

2. For the event to be labeled 'significant', wind speeds had to be sustained for at least three hours from a steady direction, which is necessary for wave build-up to occur.

3. These significant events were then sorted by peak speed and duration, yielding several potential examples of worst-case conditions.

2.3.2 Results

Table 2-1, Table 2-2, and Table 2-3 present statistical results of the screening procedure for west, south and east winds, respectively. The table columns present the percentage of samples that exceed the indicated threshold; for example column >5 m/s in Table 2-1 represents the percentage of samples where western component winds exceeded 5 m/s. Worst-case storms identified for west, south, and east winds are briefly described below.

Hurricane winds, the strongest winds to affect the region in terms of magnitude, tend to rotate in direction, and therefore do not sustain strong winds from a consistent direction long enough to develop wind-forced motions along the seabed (Driscoll 1996, Bokuniewicz and Gordon 1980b). Information on wind-speed and direction during three hurricanes is also summarized below. More information concerning these storms and the possible affect of winds on sediment transport is contained in Appendix A.

2.3.2.1 West Winds

Winds from the west are the most frequent in this region, with winter winds predominantly from the northwest and summer winds from the southwest (Williams 1969). The screening procedure described above identified several wind events featuring strong winds from the west. These events are important since west wind events are typically longer in duration than those associated with other directions, such as hurricanes or extratropical storms (northeast storms). Two events, November 17-25, 1989 and November 8-16, 1990, were identified as worst-case storms with westward winds.

The two worst-case west wind events represent the strongest west wind events in the historical data records in terms of peak speeds and event duration. The two events featured 15 to 20 m/s winds steadily from the west and persisting for several days. During the 1989 event, winds blew from the west at speeds of 5 to 10 m/s for several days before strengthening to peak conditions. Peak winds of 23 m/s were measured at the Buzzards Bay location while inland locations measured peak speeds of 17 m/s. The event persisted for about 5 days before winds weakened. The 1990 event was slightly different; weak southeast winds rotated abruptly toward the west and wind speeds increased sharply to 15 to 20 m/s. The increase in wind speeds occurred over a 24-hour period. Winds reached peak speeds of 20 to 25 m/s, and remained at these levels for about two days after which they gradually decreased. During this event, wind was steady from the west with speed exceeding 15 m/s for about three days.

2.3.2.2 South Winds

Most of the strong south wind events occurred during the winter months, and were generally weaker than west wind events. The strong southerly winds were likely caused by extratropical storms (northeast storms) whose paths dictated a prolonged period of southerly winds in the region. The strongest south wind events generally had peak speeds of approximately 20 m/s; however, the event durations were relatively short (less than a day) due to rotation of winds during the storm. This rotation suggests the passage of a low pressure system.

Two events were selected as worst-case south wind storms. Both events occurred within a few days of one another in February of 1981 and were measured at the Brookhaven, NY station. The first event occurred on February 2. It began with northwest winds around 10 m/s that weakened and turned south. These southerly winds then strengthened, (with a peak speed of 20 m/s), and remained steady from the south for about 24 hours, before rotating west and weakening. During this event, wind speeds exceeded 15 m/s for about 16 hours. The second event occurred about a week later on February 11, 1981 and featured slightly higher peak speeds (21 m/s). During this second event, the winds were not steady from a single direction but rather rotated clockwise. Wind speeds exceeded 15 m/s for about 24 hours; however, during this time winds shifted from the east to the southwest.

2.3.2.3 East Winds

Strong east wind events normally correlate with strong winter northeast storms that originate as low pressure systems in the Gulf of Mexico and progress northerly along the eastern seaboard. Strong east wind events are plentiful in the records. Two events, occurring on October 31, 1991 and December 11, 1992, were selected as worst-case east wind storms. Each of these events featured winds that began blowing from the east then rotated from the northeast. Peak speeds reached 25 m/s and the events persisted for several days. The Halloween Storm of October 31, 1991 persisted for four days, with winds exceeding 15 m/s for much of the storm. The December 11, 1992 storm shown in featured steady winds greater than 15 m/s for three full days and greater than 20 m/s for a 36 hour period.

2.3.2.4 Hurricanes

Wind speed and direction time histories for three hurricanes, Gloria in September 1985, Bob in 1991, and Floyd in 1999, were obtained from the historic wind data. These wind data were obtained from the BUZM3 station. With the exception of Hurricane Bob, whose eye passed directly over Block Island, these hurricanes were characterized by a rapid increase in wind speed and a steady rotation of winds throughout the event. The steady clockwise rotation during the storm may limit the influence winds can impart on bottom sediment transport. Winds during Hurricane Gloria exceeded 15 m/s for about 12 hours before weakening and rotated throughout the event clockwise through east, south, and west directions. Peak speeds during Gloria, as measured by BUZM3, reached 30 m/s. During hurricane Floyd on September 17, 1999 winds exceeded 15 m/s for about 24 hours, but peak speeds were lower than for other hurricanes (24 m/s). Hurricane Bob reached peak speeds of 35 m/s, with a very rapid increase in magnitude. Speeds exceeded 15 m/s for about 12 hours during the storm. This storm was unlike others in that wind direction remained steady from the south prior to the storm, then turned east and weakened. Winds accelerated rapidly as the eye passed the region, turning west as speeds peaked. Winds weakened rapidly and turned back towards the east.

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TABLE 2-1 PERCENT EXCEEDANCE FOR WEST WINDS

Location	No. of Years	>5 m/s	>10 m/s	>15 m/s	>20 m/s
Groton	31	12%	0.4%	0.01%	<0.005%
Block Island	27	19%	1.5%	0.04%	<0.005%
Brookhaven (108m)	29	25%	1.7%	0.07%	<0.005%
Buzzards Bay	12	32%	7.0%	1.05%	0.05%

TABLE 2-2 PERCENT EXCEEDANCE FOR SOUTH WINDS

Location	No. of Years	>5 m/s	>10 m/s	>15 m/s	>20 m/s
Groton	31	5%	0.3%	0.04%	0.007%
Block Island	27	11%	0.4%	0.01%	0.001%
Brookhaven (108m)	29	15%	1.3%	0.09%	0.002%
Buzzards Bay	12	25%	4.3%	0.40%	0.035%

TABLE 2-3 PERCENT EXCEEDANCE FOR EAST WINDS

Location	No. of Years	>5 m/s	>10 m/s	>15 m/s	>20 m/s
Groton	31	5%	0.2%	0.01%	0.003%
Block Island	27	5%	0.3%	0.01%	0.002%
Brookhaven (108m)	29	6%	0.4%	0.03%	0.001%
Buzzards Bay	12	11%	1.9%	0.28%	0.034%

3.0 SUMMARY OF AVAILABLE PHYSICAL OCEANOGRAPHY DATA

3.1 LONG ISLAND SOUND

3.1.1 Overview of Historical Data

Historical data from LIS and BIS were obtained and compiled from various sources. Numerous organizations were contacted as part of this process including the Long Island Sound Study (LISS) Program, the National Ocean Service (NOS), the USGS, USEPA, USACE, the City of New York, University of Connecticut (UCONN), and State University of New York (SUNY) at Stony Brook. The following major LIS and BIS physical oceanographic data sets were identified:

- NOS (1988-1990) throughout LIS and two stations in BIS
- SUNY (1989) throughout LIS
- City of New York (1995) Western LIS
- USACE (1997-1998) Eastern LIS
- UCONN (1980-present) throughout LIS

NOS, SUNY, and City of New York data sets were obtained electronically and are summarized below. The USACE 1997-1998 data were collected at the New London disposal site and are described in a draft report (SAIC 1999), but the electronic data set was not available for distribution at the time of this data collection effort (this data will become available upon publication of the final report). UCONN data were collected at numerous locations during numerous surveys. These electronic data were also not available.

Other important historical hydrodynamic data on LIS have been collected. In particular, measurements were collected to support the previous disposal site selection and evaluation processes from the 1950s through 1980s (e.g., NUSC 1979 and Nalwalk et al. 1973). In general, hydrodynamic data associated with these studies are not available electronically. Also, earlier studies resulted in relatively modest data sets compared to more recent surveys due to limitations in data collection technologies during those time periods. Some of these earlier studies featured data collection at existing disposal sites (e.g., USACE 1985 and USACE 1982) and are, therefore, useful to the present EIS process. However, since these data are not available electronically, they are not included in the Long Island Sound/Block Island Sound Physical Oceanographic Database (Electronic Attachment 2). It is recognized that other useful historic hydrodynamic data may exist.

Figure 3-1 contains a map of LIS with existing hydrodynamic data collection locations, study sponsor, and sampling location number indicated. Seasons and durations of previously collected hydrodynamic data are provided in Table 3-1. Table 3-1 presents calendar time periods and durations for each data set with the year of data collection indicated in the left column. LIS regions are color-coded as indicated in the legend. Figure 3-2 through Figure 3-5 present data sets collected during each season. Each of the data sets is summarized below.

Following the summary of each data set, specific observations of data quality, spatial coverage, and seasonal coverage of the existing hydrodynamic data in LIS are summarized (Section 3.1.1.6 through 3.1.1.8). Summaries of existing data in the Western, Central, and Eastern regions of LIS are also provided in Section 3.1.1.7. All available electronic data on LIS are included in the electronic attachment to this report, Long Island Sound/Block Island Sound Historic Physical Oceanographic Data (Unprocessed) (Electronic Attachment 5). The Long Island Sound/Block Island Sound Physical Oceanography Database (Electronic Attachment 2) also contains a compilation of this data.

3.1.1.1 National Ocean Service Data

The USEPA coordinated the multidisciplinary LISS in order to support development of a Comprehensive Conservation Management Plan (CCMP) for LIS as part of the National Estuary Program. The result of the study included the application of hydrodynamic and water quality models to explore circulation and transport processes, prediction of dissolved oxygen and nutrient distributions in the Sound, and a set of recommended actions to improve water quality. The Estuarine and Ocean Physics Branch of NOAA's National Ocean Service was tasked with acquisition of hydrodynamic data for the calibration and validation of the hydrodynamic model of LIS.

NOS conducted the Long Island Sound Oceanography Project (LISOP) from April 1988 to July 1990. Water velocity measurement locations are presented in Figure 3-6. All water velocity measurements were collected using ADCPs recording continuously and collecting measurements at one meter depth intervals throughout the water column. Table 3-2 presents the dates of water velocity meter deployments. A project summary report (Earwaker 1990) contains a complete description of LISOP data collection activities.

The LISOP program also featured collection of water level measurements at 18 locations around the shoreline of the Sound. Five of the locations support long-term water level measurement stations. Measurements were recorded at the other 13 stations for periods of 0.25 to 12 months. Water elevations were measured with one of two types of pressure gauges: analog to digital recorder gauge or nitrogen pressure driven bubbler gauge. Tide staff gauges were also installed at each location, where observers recorded daily readings. No wave gauges were deployed as part of the LISOP program.

LISOP was conducted in three phases during 1988-1990 (Earwaker 1990). Phases I and II were conducted from April 1988 to September 1989. Phase III was conducted from May to July 1990. The study area extended approximately 217 km, from the south entrance of the East River, through the East River and LIS to the outer boundaries of Block Island Sound. Table 3-3 summarizes the surveys that were conducted during each phase.

During Phases I and II of the project the following data was collected:

- Water levels at 18 stations for durations of 0.25 to 27 months;
- Water velocity time series using bottom-based ADCPs at 18 stations for durations of 1.2 to 18 months;
- Water velocity transects using boat-based ADCPs featuring multiple runs along 6 transects;
- Conductivity and temperature time series at 2 stations for durations of 2.5 to 6 months; and
- Conductivity and temperature profiles with multiple casts along 6 transects.

The following data was collected during Phase III of the project:

- Water levels at 10 stations for durations of 1.3 to 27 months;
- Water velocity time series at 4 stations for 2.5 months;
- Conductivity and temperature time series at 6 stations for 2.5 months; and
- Conductivity and temperature profiles with multiple profiles at 15 stations.

In general, data recovery was excellent. Velocity data in two of the deployments (Stations 16 and 17) were lost for approximately one day due to power failures. Some of the 1989 conductivity/temperature time-series data at the Race Rocks station were also lost. All other data were successfully recovered.

To illustrate the data collected in this survey, data from NOS08 is presented in Figure 3-7. The figures present water velocity magnitude and direction for several days at the end of July 1988. The top figure presents the observed water velocity magnitude and direction at mid-depth. The bottom figure presents the observed water velocity magnitude and direction at a near-bottom location (2 meters above bottom). Water velocities measurements shown in Figure 3-7 reach peak velocities of 60 cm/s and flow directions are primarily northeast-southwest, aligned with tidally induced flows in the Sound. Overall, the NOS data set was found to be of high quality and provides the largest set of existing hydrodynamic data of LIS.

3.1.1.2 State University of New York Stony Brook Data

The Marine Sciences Research Center of SUNY at Stony Brook, collected current data between March and October 1988 in support of the USEPA-sponsored Long Island Sound Study. The objective of the field program was to collect a hydrodynamic data set to complement the NOS data set and to support three-dimensional hydrodynamic model development and application. SUNY data was collected along 6 transects throughout LIS at locations indicated in Figure 3-8. Water velocity measurements were collected using an array of fixed-point sensors. At each transect, four vertical arrays of 2 to 4 instruments were moored across the Sound, with the uppermost instrument at least 2 m below the water surface.

Instruments were moored along each transect for approximately one month, at which time they were removed and re-deployed at the next transect. Only transects 5 and 6 were occupied simultaneously during the deployment period. Thus, the ability to compare measurements collected from different transects is reduced because they were collected non-concurrently. No tide gauges or wave gauges were deployed as part of the SUNY program.

The data collected in this study is presented in a comprehensive report (Vieira 1990) including comments on the quality and completeness of each data record and plots and summary statistics of the velocity, temperature and salinity time series data. Although each of the instruments was treated with anti-fouling paint, many of the water velocity and conductivity sensors were subject to biological fouling, particularly during the summer months. This led to erroneous data, including damped velocity measurements towards the end of the period of record or, in some cases, little or no usable data retrieval. Table 3-4 summarizes the effective recovery of the SUNY velocity data.

Despite the fairly high incidence of biological fouling of the instrumentation, the collection effort provided useful data to support characterization of circulation in the Sound. A summary and interpretation of the data is presented in Vieira (2000) and summarized in Section 2.1.

3.1.1.3 City of New York

The City of New York sponsored an extensive data collection program in New York Bight, New York Harbor and LIS to provide calibration and validation data for a system-wide eutrophication model. A water quality model was developed to explore treatment options for sewage effluent as part of a treatment facility upgrade. The field program comprised five tasks: water column monitoring, point source sample analysis, sediment flux and pore water analysis, hydrodynamic monitoring and atmospheric measurements.

The hydrodynamic monitoring program was conducted by Batelle Ocean Sciences from October 1994 to October 1995 (Fredriksson and Dragos 1996) and included data collection at locations shown in Figure 3-9 (note that only locations where velocity data was collected are shown). Instrument suites were deployed for a period of one year and included water velocity meters, tide pressure gauges and conductivity/temperature gauges. Table 3-5 presents the locations of the instrument deployments.

Bottom-based ADCP instruments were deployed at three locations: Red Hook, College Point, and Harlem River. At location H, two current meters were deployed at 3 m and 25 m in 29 meters of water.

Data recovery for the City of New York instrument deployment in LIS was generally good. The Harlem River current meter and Red Hook current meter had 100% recovery. Significant corrosion of the College Point current meter resulted in two months of data loss (November and December). Intermittent power failures resulted in some gaps (during June and July) in the data collected at location H. The data is summarized and presented in a summary report (Fredriksson and Dragos 1996).

A single tide gauge was deployed in LIS, at the west end at the mouth of the Harlem River. Measurements were made using a SeaBird SeaGage pressure sensor. Data collected at this location included sub-surface pressure, barometric pressure, temperature and conductivity. The instrument was deployed from November 1994 to November 1995, with 100% data recovery. No wave data was collected as part of the City of New York program.

3.1.1.4 United States Army Corps of Engineers Data

The USACE New England District Disposal Area Monitoring System (DAMOS) program sponsored a hydrodynamic data collection program at the New London Disposal Site in Eastern LIS in 1997 and 1998 (SAIC 1999). The investigation was conducted by Science Applications International Corporation (SAIC) and included bottom-based ADCP current profiles, near-bottom current measurements, tide and wave measurements, and boat-based synoptic ADCP current measurement surveys.

Recording hydrodynamic instruments were deployed in the northwest corner of the New London Disposal Site and collected measurements from September 19 to October 30, 1997 and from January 22 to February 27, 1998. Both deployments featured collection of near-bottom water velocity measurements and wave measurements. The winter 1998 deployment included collection of bottom-based ADCP current measurements and collection of synoptic boat-based ADCP current measurements. Maximum water velocities of 85 cm/s at near surface and 55 cm/s at near bottom locations were measured during the winter 1998 survey in the New London disposal site. The 1997/1998 USACE/SAIC New London Disposal Site data set provides the most useful hydrodynamic data collected within an existing disposal area. Unfortunately, electronic data of these measurement results are not currently available, but will be available upon publication of the report (in press).

3.1.1.5 University of Connecticut, Avery Point Data

Investigators from UCONN conducted a number of hydrodynamic data collection programs in LIS. Some of these programs were focused on collection of hydrodynamic data at existing disposal sites (Bohlen 1992). These data represent important contributions to the body of existing hydrodynamic data in LIS and should be included in the set of data presented in the EIS. However, the electronic data are presently not available.

In 1991, hydrodynamic data was collected by UCONN within the Cornfield Shoals Disposal Site (USACE 1996). Measurements were collected from mid-depth and near-bottom using fixed-point water velocity sensors. The mid-depth sensor was deployed from August to October 1991 and the near-bottom sensor was deployed from July to October of 1991.

Between 1980 and 1990, UCONN deployed near-bottom water velocity meters at disposal sites in Western, Central, and Eastern Long Island Sound (Bohlen 1992). These deployments resulted in collection of near-bottom water velocity data (at one meter above the sea floor) in each of three disposal sites. UCONN has recently and is currently collecting bottom-based ADCP measurements at various locations in LIS (Kay Howard-Strobel, personal communication).

3.1.1.6 Data Quality Summary

The NOS data set is by far the most extensive hydrodynamic data set available in the LIS region. Quality of the NOS data set was found to be generally very good and the durations of deployments typically include several tidal regimes. SUNY data was found to be of marginal quality. Large periods of recorded data are degraded by biofouling and several meters failed to collect measurement of extended periods (i.e., more than a few days). Thus, the SUNY data set appears, based on review of data coverage maps, such as Figure 3-8, to provide a more extensive data set than it actually does. The City of New York data was found to be of generally good quality and provides a solid contribution to the Western LIS region data set via the Location H data collection site. The USACE data have not been reviewed, but are believed to be of good quality and to provide a strong contribution to Eastern LIS region data set at the New London Disposal Site.

Of the major water velocity data sets, only the USACE (1997-1998) data set included concurrent wave data collection. Wave data is important in that it enables investigators to measure the effects of wave energy on near-bottom (and potentially, water-column) water velocities. The usefulness of the NOS, SUNY, UCONN, and City of New York data is diminished by the lack of concurrent wave measurements.

3.1.1.7 Spatial Coverage Summary

Existing LIS hydrodynamic data has primarily been collected at the eastern and western boundaries of the system. This is likely due to the objectives of previous studies. For example, studies performed in support of hydrodynamic modeling require strong data sets at model boundaries (e.g., the eastern and western boundary of LIS). As a result, the best characterized areas of the Sound, in terms of both the number and quality of data collection activities, are near the Race and near the East River.

Hydrodynamic data collected at these locations is not ideally suited to support EIS hydrodynamic characterizations. A summary of hydrodynamic data collection in each basin of LIS is provided below.

Western Long Island Sound Coverage

Figure 3-10 contains a map of Western LIS with locations of previous sampling activities indicated. Of existing data, the most directly applicable data appear to be City of New York data collected at location H and NOS data at locations NOS06, NOS07, and NOS08. The City of New York data was collected for a period of one year using a near-surface and a near-bottom water velocity meter (4 meters above bottom) located approximately 3 kilometers northeast of the Western Long Island Sound Disposal Site. NOS data at locations 6, 7, and 8 were collected during late spring and summer seasons when worst-case storm conditions are least likely to occur. These stations are generally located in areas unsuitable for dredged material disposal. For example, Station 8 is located in the relatively deep main channel where relatively high bottom velocities would be expected.

SUNY data collected along transect #2 during the spring season are also available. Sparse data are available at or near the Western LIS disposal sites. In the late 1970’s and early 1980’s, limited data were collected at several disposal sites in Western LIS (USACE 1982). These data are of limited utility to the present study due to instrumentation limitations and the brevity of the deployments. The extent and quality of previously collected Western LIS hydrodynamic data is likely not sufficient to support the present EIS.

Central Long Island Sound Coverage

Figure 3-11 contains a map of Central LIS with locations of previous sampling activities indicated. A paucity of data has been collected in the Central LIS region. In total, SUNY transect #4 and NOS locations 9 and 10 were deployed in this area. Both the SUNY and NOS data collection activities in Central LIS were performed during the summer season when worst-case storm events are least likely to occur. Also, the NOS stations were located in the relatively deep main channel where relatively high bottom velocities would be expected and therefore the data is not representative of areas that would be suitable for designation of a disposal site. The Central LIS region is large and, potentially well-suited for disposal site designation. Thus, it is unfortunate that so little data is available in this region.

Relatively little hydrodynamic data has been collected in Central LIS compared to the Eastern and Western regions. No recent and available hydrodynamic data have been collected in Central LIS during the fall, winter, or spring season. Existing data does not provide good spatial coverage of the Central region. For example, there is no available hydrodynamic data over the entire width of the Sound between the Central Long Island Sound Disposal Site and Long Sand Shoal, except for at NOS location NOS10 (and, as discussed above, data from this station is not representative of locations suitable for designation of a disposal site). Thus, over an area of approximately 1200 km^2 (40km by 30km), only one data set is available to support hydrodynamic characterization. Sparse data are available at or near the Central Long Island Sound Disposal Site. In the late 1970's and early 1980's, limited data were collected at Central LIS (USACE 1985). These data are of limited utility due the quality of the instrumentation and brevity of the deployments. The extent and quality of previously collected Central LIS hydrodynamic data is likely not sufficient to support the present EIS.

Eastern Long Island Sound Coverage

Figure 3-12 contains a map of Eastern LIS with locations of previous sampling activities indicated. Hydrodynamics have been relatively well characterized in Eastern LIS compared to the Central and Western regions. Six NOS sampling locations, six SUNY sampling locations, one USACE sampling location, and UCONN sampling locations have been situated in the Eastern LIS region.

Hydrodynamic measurements have been collected at the New London Disposal Site and at the Cornfield Shoals Disposal Site in the 1990's (USACE 1997-1998 and UCONN 1991). Of existing data, the USACE data in the New London Disposal Site is most useful because it was collected during the winter season and included wave and near-bottom water velocity measurements. The existing New London and Cornfield Shoals Disposal Site data sets may be sufficient to support the present EIS.

Relatively strong currents throughout most of the eastern region have been well documented. Strong currents in Eastern LIS are credited with creating a non-depositional sedimentary environment throughout much of the region. Thus, much of the Eastern LIS region is likely not suitable for designation of disposal sites due to unfavorable hydrodynamic conditions, though areas that may be more protected, such as in the area of the New London disposal site, may have more suitable hydrodynamics.

3.1.1.8 Seasonal Coverage Summary

Hydrodynamic data collected during the fall, winter, and spring season are most useful to support the EIS evaluation because "worst-case" storm events tend to occur during these seasons. As shown in Figure 3-4, relatively little data have been collected during the fall season in LIS. No data have been collected in the Central region during these seasons and only the location H data (City of New York, 1995) has been collected in the Western region. SUNY and NOS data were collected in the Eastern region during the fall season, but not near the existing disposal area. USACE/SAIC data collected at the New London Disposal Site are most useful for characterizing the fall/winter hydrodynamic characteristics of the Eastern region.

The largest seasonal data set was collected during the summer (Figure 3-3). In general, data from this season is least useful to support the EIS because disposal events generally do not occur during the summer season and “worst-case” hydrodynamic conditions are least likely to occur during the summer season.

The occurrence of storm events during deployments affects the usefulness of the data collected. Specifically, data collected during “worst-case” storm events is highly valuable to the present EIS. For all major existing data sets, available wind and wave height data was obtained and reviewed for the historic deployment periods to provide storm event context. Storm event contextual information provides a more detailed characterization of the existing data set relative to the requirements of the present EIS.

3.1.2 Analysis of Previously Collected Data

3.1.2.1 Data Analysis Approach

An analysis of NOS data was performed to support the LIS EIS. NOS data were selected for analysis because these data are the most applicable to support the EIS and because comprehensive analysis and documentation of these data have not previously been published. SUNY and City of New York data have been previously analyzed and documented. For the SUNY data, summaries, including graphs and statistical tables, may be found in Viera (1990). For the City of New York data, summaries may be found in Fredriksson and Dragos (1996). These reports include visual representations of the data and Viera (2000) presents an analysis of the SUNY data.

Data processing and analyses were performed on the NOS physical oceanographic data set. In general, NOS data collection locations do not meet the EIS project objectives because most of the locations are not situated in areas suitable for designation of a disposal site. Numerous NOS sampling locations are near in the East River, along the central axis of LIS, or near The Race. All of these locations are likely not suitable for designation of a disposal site because of expected strong currents. Some NOS sampling location, however, are situated in potentially suitable locations and were a focus of this evaluation.

Data analysis tasks focused on using the data to evaluate critically important characteristics relative to the LIS EIS process. Several characteristics of the physical oceanographic data set were deemed to be critically important including the following:

- *Water column water velocity data set to support assessment of potential for dredged material dispersion and transport during disposal events.* Maximum total water velocities were measured throughout the water column during the NOS survey. These data may be applied to assess the potential for sediment transport during potential dredged material disposal events. Evaluation of maximum water column water velocities provides insights into the feasibility of successfully transporting dredged material from a barge to the sea floor at selected locations.

- *Near-bottom water velocity data set to support assessment of potential for dredged material re-suspension and transport from the sea floor.* Maximum near-bottom total water velocities were measured during NOS survey. These data are important in assessing the potential for sediment re-suspension and transport away from the potential disposal sites. Evaluation of maximum total water velocities near the sea floor provides insights into the feasibility of retaining dredge material at the disposal site.

Data analyses focused on assessment of the factors leading to maximum near-bottom water velocity conditions at each location. Two data analysis tasks were performed to support evaluation of maximum near-bottom hydrodynamic conditions.

First, since maximum water velocity conditions occur when maxima for all components of total water velocity are realized, an evaluation of tidal, wind, and storm-driven current was conducted. It is important to characterize maximum water velocities associated with each of these components of the total water velocity in order to better estimate the magnitude of worst-case (i.e., maximum) total near-bottom currents. For example, a maximum near-bottom water velocity may be estimated as the sum of velocity components from spring tidal forcings and a maximum wind forcing at the specific location. Thus, the first task focused in decomposing water velocity measurements obtained during the NOS survey with the goal of evaluating potential worst-case (i.e., maximum) conditions. Statistical analyses were also performed to support evaluation of the likelihood of occurrence of such worst-case scenarios.

Secondly, wind data measured concurrently with the survey period were reviewed and relatively high wind events identified. Water velocity data collected during relatively high wind events were evaluated and the relationship between wind speed and direction and near-bottom water velocity was quantified. The wind evaluation task was conducted to support development of maximum wind-driven near-bottom water velocity components throughout the study domain.

The additional data analysis tasks were conducted to support evaluation of maximum near-bottom water velocity conditions at each sampling location. Clearly, the total water velocities measured during the field investigation are of primary value. Decomposition of water velocity components is also a valuable exercise to support determination of potential worst-case or maximum water velocity conditions.

3.1.2.2 Data Analysis Methods

The entire NOS data set was analyzed to support the EIS. Representative stations from each basin are presented in this section and are discussed in detail (Table 3-6). A complete set of figures for each station and each deployment are presented in Electronic Attachment 4, Long Island Sound/Block Island Sound Physical Oceanographic Data and Analysis: Plots. For the stations discussed in this section, the following figures are presented:

- Time series of currents for the duration of the deployment, including magnitude and directions and V_x and V_y components.
- Tidal ellipses of the M_2 tidal component at the surface, middle and bottom bins.
- Decomposition of the current into tidal, sub-tidal, and high-frequency components.
- Analysis of two wind events.
- Time series of tidal and sub-tidal currents.
- Wind and current rose diagrams.

The two wind events were identified by examining the concurrent wind record from the NOAA weather station BUZ3M, located in Buzzards Bay, MA over the course of the NOS deployments, and identifying storms where winds were equal to or greater than 8 m/s, and were sustained for 24 hours or more. Not all of the stations had active deployments that coincided with these wind events.

3.1.2.3 Data Analysis Results and Interpretation

Water Velocity Magnitude and Direction

Time series figures of predicted water surface elevation, wind magnitude and direction, and water velocity magnitude and direction are presented in Figures 3-13 through 3-17. Time series plots of predicted water surface elevation, wind magnitude and direction and V_x and V_y are presented in Figures 3-18 through 3-22. Current rose diagrams at surface, middle and bottom depths are presented in Figures 3-23 through 3-27. Note that the deployments at each station occurred at different times during the 18 month study period (See Table 3-6). Water surface elevation was not collected as part of the NOS study, thus the water surface elevation was predicted from the tidal harmonics obtained in the analysis of ENSR's 2001 data (see Section 5). The closest ENSR station was chosen for water surface elevation predictions for each NOS station.

Maximum water velocity magnitudes within the entire water column measured at the NOS stations ranged from 50 cm/s in Western LIS and Central LIS to 150 cm/s in Eastern LIS. In the three basins within the Sound, water velocity magnitude followed the spring-neap tidal cycle, with stronger currents observed during the spring tide. The effect of wind was observed on the surface currents, where strong (greater than 15 m/s) winds caused increases in surface currents. See NOSO8 on 9/5/88 (Figures 3-14 and 3-19) for an example of these dynamic events.

At NOS07 in Western LIS, the maximum surface current magnitude was 70 cm/s and maximum bottom current magnitude was approximately 50 cm/s (Figure 3-13). Currents in the x-direction (east-west) were observed to be generally higher than those in the y-direction (north-south) (Figure 3-18). Maximum east-west surface currents were approximately 40 to 50 cm/s, with maximum westward currents during the spring tide. Maximum east-west bottom currents were approximately 20 cm/s in both directions. Maximum currents in the north-south direction were approximately 15 cm/s, except for bottom currents in the southerly direction, which attain a maximum speed of approximately 50 cm/s. The southern currents were observed to be consistent with model predictions of a counter-clockwise gyre within Western LIS (Schmalz 1993).

The dominant current direction at NOS07 in Western LIS was observed to be generally east-northeast to west-southwest (Figure 3-23). At all depths, currents were generally in phase, or flowed in the same direction at the same time. Bottom current direction was northeast to southwest, and currents flowed to the southwest the majority of the time. Current direction was clearly dominated by tidal influence, although surface current direction was the most variable, likely due to wind influences.

NOS08 is located at approximately the boundary between Western LIS and Central LIS, and NOS09 is located in the center of Central LIS. Both Stations NOS08 and NOS09 are situated along the relatively deep main axis of LIS and exhibited similar current magnitudes. Maximum surface and bottom current magnitudes at both locations were observed to be approximately 60 cm/s (Figures 3-14 and 3-15). Bottom current magnitudes were generally highest during the spring tide. The x-direction (east-west) maximum current speed was approximately 40-50 cm/s (Figures 3-19 and 3-20). The y-direction (north-south) current was much smaller, with maximum speeds of approximately 10 to 20 cm/s.

At NOS08, the dominant current direction was generally northeast-west at the surface and middle depths, and east-northwest at the bottom (Figure 3-24). At NOS08 surface and bottom, there was a higher percentage of currents in the easterly direction, while at mid-depth, there was a higher percentage of currents in the westerly directions. At NOS09 in Central LIS, the dominant current direction was east-west at all depths (Figure 3-25). At the surface, the percentage of currents in the east direction was slightly greater, at the middle depth the east-west distribution was split almost equally, and at the bottom the percentage of currents in the west direction was greater. These observations are consistent with estuarine-like circulation that have been previously observed and modeled in LIS.

In Eastern LIS, at NOS13 and NOS21, current magnitudes were observed to be considerably higher than those observed in Western LIS and Central LIS. Maximum surface current magnitudes were approximately 120 cm/s (Figures 3-16 and 3-17), and maximum bottom current magnitudes were approximately 75 cm/s (at NOS13) to 100 cm/s (at NOS21). Currents were approximately 50% higher during the spring tide. Maximum currents in the x-direction (east-west) were 100 cm/s at the surface and 50-82 cm/s at the bottom. At NOS13, surface currents were stronger to the east and bottom currents were stronger to the west. At NOS21, bottom currents were slightly stronger to the west, while surface currents were approximately equal in both directions. Currents in the y-direction (north-south) were about one-half the speed of the north-south currents (Figures 3-21 and 3-22).

In Eastern LIS, the dominant flow directions appeared to be aligned with the local bathymetry. At NOS13, the dominant flow direction was southeast-northwest at all depths (Figure 3-26). At NOS21, the dominant flow direction at the surface was east-west, in the middle east-northeast to west-southwest, and at the bottom currents flowed primarily to the northeast, with some flow to the west (Figure 3-27). At NOS13, the north-south currents were generally in phase at all depths, or flowed in the same direction at the same time. At NOS21, the surface currents were slightly out of phase with the middle and bottom currents.

It should be noted that several of the NOS stations in Western LIS and Central LIS (i.e. NOS07, NOS08, NOS09, and NOS10) were located in areas where relatively high maximum bottom velocities would be expected (e.g., along the main axis of the Sound). Therefore, the bottom velocities discussed above are expected to be higher than at other locations within Western LIS and Central LIS that may be suitable for designation of a disposal site. In fact, lower values have previously been measured during other studies. For example, at NOS station NOS09 (with a depth >40 m) in Central LIS the maximum measured bottom currents were 60 cm/s, while the maximum near-bottom (3 m above bottom) currents measured at Station 4NC (depth of 18.3 m) in a Central LIS transect during a study by SUNY (Viera 1990) was 34.7 cm/s.

<u>Water Velocity Decomposition</u>

Total water velocity data were decomposed into component velocities to support evaluation of potential maximum water velocity conditions. The goal of water velocity decomposition was to support evaluation of maximum total water velocity or worst-case conditions by quantifying maxima for each component of total water velocity. A worst-case total water velocity may then be estimated by summing maximum values for each velocity component. Worst-case water velocity conditions are defined as conditions most likely to result in transport of dredged material. The probability of occurrence of maximum water velocities was also evaluated to support specification of reasonable worst-case scenarios.

The total water velocity signal may be decomposed into several components, including tidal, high-frequency (generally associated with noise) and subtidal, which contains forcing from wind, density driven currents, and other forcing functions that are greater than a 33-hour period. Once decomposed, the components of the current may be analyzed to determine the dominant forces driving current magnitude. Two methods of analyzing the decomposed data were applied and are presented below.

To decompose the current, the tidal harmonics were determined by curve fitting. Once the 33 tidal harmonic constituents were determined, the tidal current was separated from the total current. Tidal ellipses provide a graphical representation of the tidal current. The remaining, or residual, current, is then run through a 33-hour low pass filter to remove high-frequency noise. This high-frequency signal can result from turbulence, wave induced flow or measurement noise (e.g. mooring interference). The remaining subtidal current represents currents due to wind, freshwater inflow, seasonal variations and density driven currents. For long records (greater than 60 days) the wind signal can be removed from the remaining subtidal signal.

Figures 3-28 through 3-32 present the tidal ellipses of the M_2, or dominant, tidal component at surface, middle and bottom depths. The tidal ellipse parameters are presented in Table 3-7. All of the ellipses were narrow, indicating little flow normal to the dominant flow direction (east-west). The widest ellipse was found in Western LIS at the surface. In general, the ellipses at the three depths were aligned, or in the same direction. A slight clockwise rotation with depth was observed in Western LIS, and at NOS21 in Eastern LIS, as the dominant current direction shifts. In all locations, the maximum surface and middle water velocity magnitude was similar, while bottom water velocities were lower. At all locations, the bottom ellipse was observed to rotate in the opposite direction as the surface ellipse, indicating rotational flow in opposing directions.

Table 3-7 presents the percent of current variation captured by the M_2 tidal current. In Western LIS, at stations NOS02, NOS03 and NOS06, most of the x-direction variation was captured by the tidal current. At NOS01, much of the current variation in the y-direction was captured by the tidal current variation, indicating that the dominant direction of flow at this location was in the north-south direction. In Central LIS and Eastern LIS, almost all current variation in the x-direction at all depths was captured by the tidal current, while less y-direction variation was captured. Other factors that contribute to current variation include bathymetry, freshwater inflow, wind, and other tidal harmonics.

A time series of the decomposition of the bottom current components is presented in Figures 3-33 through 3-37, including total current, tidal current, residual current, sub-tidal current and high frequency noise (sub-tidal and high frequency sum to residual). These figures indicate that the majority of the current energy was from the tides. The residual current was generally less that 50% of the total current. At several stations (NOS08, NOS13, and NOS21), the sub-tidal frequency signal was lower than the high-frequency signal, indicating little wind effects over the deployment period.

At NOS07 in Eastern LIS, the tidal current was approximately 75% of the total current (Figure 3-33). The maximum tidal current was 50 cm/s, the maximum sub-tidal current was approximately 25 cm/s and the maximum high-frequency current was 20 cm/s. The sub-tidal signal was approximately double the high-frequency signal. These results suggest that winds or density gradients may have been driving currents in this location.

At NOS08 and NOS09 in Central LIS, the maximum tidal current was 40 cm/s, the maximum sub-tidal current was 15 cm/s and the maximum high-frequency current was approximately 20 cm/s (Figures 3-34 and 3-35). At both stations, the magnitude of the high frequency signal was on the order of the sub-tidal signal, and at both stations the sub-tidal signal was generally lower than that observed in Western LIS.

In Eastern LIS, bottom current components at NOS13 and NOS21 were observed to behave quite differently. At NOS13, the tidal current comprised the majority of the total current (Figure 3-36). The residual current at NOS13 was less than half that at NOS21. The high percentage of total current that was tidal at NOS13 may have been due to the location of the station, in the narrow Race, where currents are focussed by the bathymetric structure. The maximum tidal current at NOS13 was 62 cm/s, the maximum sub-tidal current was 10 cm/s and the maximum high-frequency current was 18 cm/s. At NOS21, the maximum tidal current was 95 cm/s, the maximum sub-tidal current was 30 cm/s, and the maximum high-frequency current was greater than 20 cm/s (Figure 3-37).

3.1.2.4 Wind Events

The wind data record concurrent with the NOS survey was reviewed and two relatively high wind events were selected and evaluated. Wind events are of interest because associated wind-driven water velocities, together with tidal-driven and other velocity components, sum to result in maximum or worst-case hydrodynamic conditions in terms of potential for dredged material transport. Thus, wind events were analyzed to enhance understanding of the wind-driven component of total water velocity in support evaluation of maximum total water velocity conditions. Water velocity data associated with two wind events that occurred during the study period were selected and analyzed and are presented below.

<u>August 1988 Wind Event</u>

The first wind event identified in the record occurred on August 14-16, 1988. The maximum wind speed during this event was 17 m/s, and winds greater than 10 m/s were sustained for approximately 30 hours. The wind was consistently out of the southwest (blowing towards the northeast) for the duration of the event. Water velocity measurements were collected at NOS08 and NOS09 during the August 1988 wind event.

Figures 3-38 through 3-43 present data associated with the August 1988 wind event. Figures 3-38 and 3-39 present time series plots of predicted water surface elevation, wind magnitude and direction, and water velocity magnitude and direction. Figures 3-40 and 3-41 present time series plots of predicted water surface elevation, wind magnitude and direction, and sub-tidal water velocity magnitude and direction. Figures 3-42 and 3-43 present wind and sub-tidal water current rose diagrams for NOS08 and NOS09, respectively.

Surface water velocities at NOS08 and NOS09 did not appear to increase in response to the August 1988 wind event (Figures 3-38 and 3-39). Water velocity magnitudes at all depths were comparable to those observed over the course of the deployment. Sub-tidal water velocity magnitudes remained constant (~10 cm/s) throughout the wind event at all depths. The maximum bottom currents were approximately 50 cm/s at NOS08 and 35 cm/s at NOS09.

The sub-tidal current directions were out of phase with depth (i.e., flowing in different directions at different depths). At NOS09, the middle sub-tidal current was 180º out of phase with the surface and bottom subtidal current. At NOS08, the surface current was 180º out of phase with the middle and bottom current for the duration of the wind event and became aligned with the middle and bottom as the wind tapered off. The maximum bottom sub-tidal water velocities were approximately 15 cm/s at NOS08 and 10 cm/s at NOS09.

At NOS08, the sub-tidal surface current was oriented towards the northeast, slightly to the right of the wind (Figure 3-42). Sub-tidal surface currents at NOS09 were oriented to the east and southeast, clockwise of the wind direction (Figure 3-43). The sub-tidal surface current direction may have been the result of Ekman shear. The Coriolus forces, which are directed at a right angle to the wind forcing, result in current directions that are to the right of the wind on the surface (Ekman shear), and continue to rotate to the right with depth into the water column (Ekman spiral). Sub-tidal bottom currents at NOS09 were observed to be oriented to the northwest and rotated to the right of the surface currents, suggestive of an Ekman spiral. Bottom currents at NOS08 were to the northeast, in the direction of the wind.

<u>September 1988 Wind Event</u>

A second wind event occurred on September 4-6, 1988. The maximum speed during this event was 16 m/s, and winds greater than 10 m/s were sustained for approximately 28 hours. Winds were out of the west-southwest (blowing to the east-northeast) for the duration of the event. NOS stations NOS08 and NOS09 were deployed during this event. This event occurred during the neap portion of the tidal cycle.

Figures 3-44 to 3-49 present data associated with the September 1988 wind event. Figures 3-44 and 3-45 present time series plots of predicted water surface elevation, wind magnitude and direction, and water velocity magnitude and direction. Figures 3-46 and 3-47 present time series plots of predicted water surface elevation, wind magnitude and direction, and sub-tidal water velocity magnitude and direction. Figures 3-48 and 3-49 present wind and current rose diagrams for NOS08 and NOS09, respectively.

At NOS08, the total and sub-tidal surface water velocity magnitude was slightly increased due to wind forcings (Figures 3-44 and 3-46). At the middle and bottom depths, there was no noticeable increase in water velocity magnitude resulting from the wind event. At NOS09, the water velocity magnitudes did not appear to increase due to the wind forcing (Figures 3-45 and 3-47). The maximum bottom current speeds were approximately 40 cm/s at both stations.

At NOS08, the sub-tidal surface and bottom current directions were in phase, but out of phase with the middle current direction, similar to the sub-tidal current directions at NOS09 during the August 1988 wind event. At NOS09, the sub-tidal current directions were aligned with depth. The maximum sub-tidal water velocity magnitudes were approximately 10 cm/s at NOS08 and 12 cm/s at NOS09. The varied response of the two stations to similar wind events suggests that other factors were contributing to sub-tidal flows (e.g. spring-neap tidal cycle).

The current rose diagrams for surface and bottom sub-tidal currents at NOS08 are similar to those presented the August 1988 wind event, with the dominant current direction at both surface and bottom towards the northeast. At NOS09, both surface and bottom sub-tidal currents were oriented towards the west and northwest. Bottom currents were oriented in the same direction as for the August 1988 wind event, but surface currents were oriented in the opposite direction.

3.2 BLOCK ISLAND SOUND

Previously available data for BIS is adequate to support a general description of the physical oceanographic characteristics (as provided below). However, the data is limited in both spatial and temporal extent and would not be adequate to support the EIS process for designation of a dredged material disposal site.

Block Island Sound is vertically stratified in summer and well-mixed in winter. Vertical salinity gradients of approximately 2 ppt were observed in summer, ranging from 30.6 ppt (surface) to 32.4 ppt (bottom), and were negligible in winter (Ayer and Stockton 1952). Stability of the water column is maximized during stratified conditions in summer, inhibiting vertical mixing, and minimized in transitional periods such as April and October-November, when winds and seasonal cooling serve to eliminate vertical density gradients. The strength of tides within the region affects vertical stability, resulting in zones of strong stratification in areas of less intense tidal currents, and vertically homogenous waters in areas of strong tidal mixing. Strong stratification existed over the northern/central region of the Sound, but low stability was noted within the tidal channels (The Race, Block Island Channel) and Endeavor and Southwest Shoals (Bowman and Esaias 1981).

Figures 2-7 and 2-8 show flood and ebb tidal currents, respectively in BIS. Semi-diurnal tidal currents dominate BIS circulation, accounting for as much as 92% of the overall current energy (Snooks and Jacobsen 1979). The strongest currents are found through the principal channels: The Race, Plum Gut, and Block Island Channel. Currents in The Race can exceed 5 knots (US Coast and Geodetic Survey 1958), while those in Plum Gut have been charted at 4.5 knots. Maximum currents through Block Island Channel are of order 2.5 knots, and around Montauk Point can reach nearly 3 knots. Snooks and Jacobsen (1979) measured a maximum current of approximately 1.7 knots through the passage between Rhode Island Sound and BIS; US Coast and Geodetic Survey tide charts show ebb currents reaching a maximum of 2.5 knots just north of Sandy Point, Block Island.

Tidal currents were found to be strongest in the center of the channels and near the surface, with weaker currents near frictional boundaries such as the seafloor and shoreline (Snooks and Jacobsen 1979). There is evidence of localized flow accelerations around headlands (US Coast and Geodetic Survey 1958), specifically Sandy Point, Point Judith, and Montauk Point.

The tide is asymmetric within these channels, with the ebb tide duration generally longer than the duration of the flood tide. US Coast and Geodetic Survey Tide Charts, whose graphical depiction of current patterns within BIS likely refer to surface currents, not bottom currents, present that the ebb duration for The Race is 6 hours 36 minutes, while the flood duration is 5 hours 49 minutes. Tidal asymmetry within enclosed estuaries usually classifies the system into either ebb-dominance or flood-dominance (Freidrichs and Aubrey 1988), depending on the duration of the tide phase. A longer duration ebb tide and a short flood typically implies strong flood currents and relatively weaker ebb currents, conserving mass into and out of the enclosed embayment. However, the Race has a longer duration ebb tide and swifter ebb currents, suggesting that there is a net transport in the surface layer out of LIS into BIS as discussed below.

Evidence of a large-scale transient eddy was found from surface current observations. This eddy results perhaps from brief horizontal shear at the end of the flood tide phase. The onset of ebb tide is evidenced initially eastward out of Napeague Bay along the north shore of Montauk (Figure 2-9). However, the greater momentum of the northwestward flood tide through Block Island Channel requires some phase lag before reversing. This brief phase of the tide characterized by eastward flow at Montauk and northwestward flow within the Channel, sets up a horizontal shear and results in a large-scale eddy. This eddy has a length scale of approximately 10-15 nautical miles in diameter, of similar length scale to BIS as a whole.

Currents that vary over time scales greater than diurnal tides (about one day) are termed subtidal currents. These currents, also termed residual drift, can be responsible for long-term distribution of sediments and effluents. Processes generally responsible for subtidal currents include winds, storms, density variations, residual currents due to tidal asymmetry, and low-frequency oscillations found on the continental shelf.

Sub-tidal flow analysis (Snook and Jacobsen 1979) indicates a two-layer estuarine system, with the upper surface responding strongly to wind stress, and the lower layer correlated more strongly to tidal asymmetry. In general, the upper layer showed a net eastward drift, exiting BIS, consistent with prevailing winds from the southwest (in spring and summer) and the northwest (in winter). The lower layer (near bottom) showed a net westward drift, into the estuary. Bokuniewicz and Gordon (1980) reported that bottom flow in LIS was correlated to winds only about 0.009% of the time; most of the energy of sub-tidal bottom flow could be traced to processes originating on the shelf or BIS.

Vertical density variations may also be responsible, or contribute to this two-layer flow pattern. Denser shelf waters flood into the Sound along the bottom, mix with slightly fresher water from LIS, and exit as lighter water closer to the surface. Another possible driving force for bottom currents over subtidal time scales may be shelf waves that propagate into BIS. Noble et al. (1983) described aperiodic shelf waves that propagate counterclockwise from Georges Bank to the Mid-Atlantic Bight. These subtidal shelf waves accounted for nearly 75-90% of the longshelf current energy, and may enter BIS, affecting bottom currents.

The literature indicates that the wave field within much of BIS is locally-generated, and that waves affect bottom sediments in just a few locations. Long-period waves generated remotely within the Atlantic are dissipated by the shallow ridge between Montauk Point and Block Island. The presence of large sand waves northeast of Montauk Point as well as gravel/boulders atop Southwest Ledge offers evidence of wave scour and sediment transport processes at these locations. The other location where waves may be important to bottom currents is near the Rhode Island shoreline where swell from the east and southeast can enter the Sound. The largest waves observed in the Sound are when east winds generate wind waves and combine with an ocean swell. Waves of 20 feet have been observed (Williams 1969).

3.3 SUMMARY

Existing hydrodynamic data in LIS is generally suited to support Sound-wide hydrodynamic characterizations and modeling applications. In general, the existing data set is not as well-suited to support the EIS hydrodynamic evaluation. Also, limited hydrodynamic data exists for BIS. Major data gaps identified in the review of existing data include the following:

- Little data collection activities focused on measurement of hydrodynamic conditions during storm events in the Sound;
- Little wave data collected along with current measurements;
- Little data collected concurrently at different locations to support spatial characterization and comparison of hydrodynamic conditions.
- Little data collected in the Central Basin region in general and no recent data collected in the Central region during the fall/winter season.
- Little data collected at the Western Long Island Sound and Central Long Island Sound Disposal Sites, particularly at locations suitable for dredge material disposal; and
- Limited data exists for BIS.

Data collection activities performed during the Spring 2001 study were designed to address the data gaps identified above.

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TABLE 3-1 SEASONAL HYDRODYNAMIC DATA COLLECTION SUMMARY

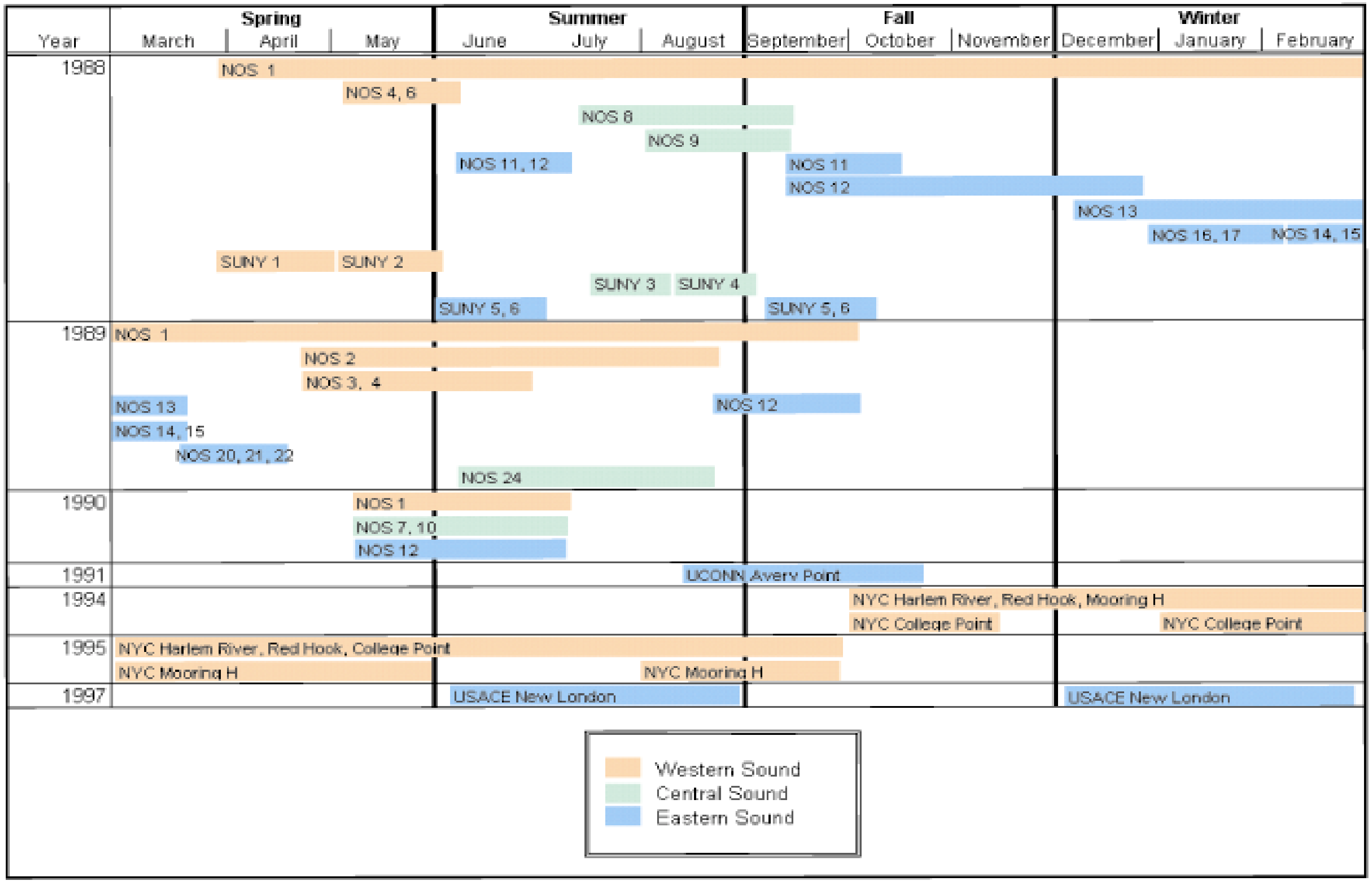

TABLE 3-2 DATES OF NOS DEPLOYMENTS

Station	Dates of Deployment
1	3/30/88-10/3/89*, 5/7/90-7/17/90
2	4/24/89-8/22/89
3	4/24/89-6/5/89
4	5/3/88-6/7/88, 4/24/89-6/5/89
6	5/3/88-6/7/88
7	5/7/90-7/17-90
8	7/14/88-9/13/88
9	8/2/88-9/13/88
10	5/6/90-7/18/90
11	6/9/88-7/13/88, 9/14/88-10/20/88
12	6/7/88-7/12/88. 9/14/88-12/29/88, 8/24/89-10/2/89, 5/6/90-7/18/90
13	12/7/88-3/14/89
14	2/10/89-3/16/89
15	2/10/89-3/15/89
16	12/30/88-2/8/89*
17	12/30/88-2/8/89*
20	3/17/89-4/20/89
21	3/17/89-4/20/89
22	3/17/89-4/20/89
24	6/6/89-8/22/89
*Record not inclusive for period	

TABLE 3-3 SUMMARY OF NOS DATA COLLECTION ACTIVITIES

Survey	Phase I	Phase II	Phase III
Water level measurements	X	X	X
Current measurements	X	X	X
Conductivity and temperature time series		X	X
Conductivity and temperature vertical profiles			X

TABLE 3-4 SUMMARY OF SUNY VELOCITY DATA RECOVERY

Transect	Dates	No. of Instruments	Complete Velocity Records	Partial Velocity Records
1	3/28/88-5/2/88	14	8	5
2	5/2/88-6/1/88	10	7	2
3	7/14/88-8/9/88	11	5	6
4	8/10/88-9/7/88	13	5	8
5	6/1/88-7/5/88	7	3	1
	9/8/88-10/14/88	8	3	4
6	6/1/88-7/5/88	7	4	2
	9/8/88-10/14/88	9	7	1

TABLE 3-5 SUMMARY OF CITY OF NEW YORK METER DEPLOYMENTS

Location	Current Meter	Conductivity/Temperature Meter	Water Level
Harlem River	**X**[1]		
Harlem River Tide			**X**
Red Hook	**X**[1]		
College Point	**X**[1]		
Location H	**X**[2]	**X**	
Notes: [1] Profile measurements [2] Near-surface and near-bottom measurements			

TABLE 3-6 NOS STATIONS PRESENTED IN DETAILED ANALYSIS

Station	Location	Season
NOS07	Western LIS	Summer
NOS08	Central LIS	Summer
NOS09	Central LIS	Summer
NOS13	Eastern LIS	Winter
NOS21	Eastern LIS	Spring